VOL. 15 No. 3, pp. 73-104 SEPTEMBER 1953

# Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
THE PHILIPS INDUSTRIES

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, NETHERLANDS

## THE FERROXCUBE TRANSFORMER CORE USED IN THE BROOKHAVEN COSMOTRON

by F. G. BROCKMAN *) and M. W. LOUWERSE **). 621.318.134: 621.384.61

*For the last ten or twenty years fundamental research in nuclear physics has been associated with the building of ever larger machines for particle acceleration. This evolution which has tied up the physicist's work with that of the engineer has frequently been commented on. However, the evolution continues, and in recent years the personal assistance of the engineer has been superseded by the material cooperation of whole industrial organizations. This article will give an account of the cooperative studies that have been made in the development of ferrites for high energy particle accelerators by the Brookhaven National Laboratories, U.S.A., and the Philips Laboratories in the Netherlands and the U.S.A.*

### Introduction

In the efforts to produce particles of very high energies for nuclear experiments, a substantial advance was made in the past year when the proton accelerator of the Brookhaven National Laboratories, U.S.A. — the Cosmotron — was brought into successful operation. While the highest particle energy obtained with earlier accelerators did not surpass 1000 million electron volts, the Cosmotron has produced protons with 2300 MeV, and it is expected that the energy can be increased to 3000 MeV.

The completion of this machine, which was achieved by a group of workers including M. S. Livingston, J. P. Blewett, G. K. Green and L. J. Haworth, is a remarkable feat of enterprise and engineering. A few data that will be mentioned presently may give some idea of the vastness of the project. An account of the design was given by these Brookhaven workers in 1950 in the Review of Scientific Instruments, and a detailed description of the completed machine has just appeared in the same journal [1]).

The present article will focus attention on the fact that, in one of the chief elements of the Cosmotron, the "transformer" producing the radio-frequency electric field for the actual acceleration of the protons, a large ferrite core plays an important part. The major portion of this core was assembled from Ferroxcube material manufactured by Philips at Eindhoven. The specifications for this core and the problems encountered in selecting the material and in the manufacturing will be described. A few remarks will be made on the development of other ferrite materials for similar purposes.

### Basic design of the Cosmotron

A short description of the design principles of the Cosmotron as published in the first article quoted in [1]), will first be given.

The protons travel in an annular evacuated chamber of cross-section $30'' \times 7''$. This chamber is composed of four quadrants of about 30 feet radius, which are connected together by four short straight sections (plan view, *fig. 1*). The protons are made to follow a path roughly on the axis of the chamber by magnetic fields perpendicular to the plane of the path, which are produced by four powerful electromagnets disposed along the path. In the photograph of the Cosmotron (*fig. 2*) the yokes of these magnets, which enclose the annular acceleration chamber, can be seen.

---

*) Philips Laboratories, Inc., Irvington-on-Hudson, N.Y., U.S.A.
**) Laboratory of the Philips Ceramics Factory, Eindhoven, Netherlands.
[1]) M. S. Livingston, J. P. Blewett, G. K. Green and L. J. Haworth, Design study for a three-Bev proton accelerator, Rev. sci. Instr. **21**, 7-22, 1950.
The detailed description is contained in a series of articles in Rev. sci. Instr. **24**, 723-870, 1953 (No. 9).

One of the straight field-free sections is used for the injection of the protons into the chamber. The protons are obtained from a hydrogen ion source and accelerated by a Van de Graaff high voltage generator to an initial energy of 3.5 MeV for injection. In another straight section the acceleration of the injected protons is effected: under the influence of a longitudinal electric field alternating at a suitable frequency, their energy is increased by a certain amount after every revolution. To keep the protons (mass $M$, charge $e$) on a circular path of radius $R$, a magnetic field of flux density

$$B = \frac{Mv}{eR} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

is required. With the momentum $Mv$ corresponding to the *initial* energy of 3.5 MeV, the required value of $B$ is 0.029 Wb/m$^2$. In order to keep the protons on the same orbit within the vacuum chamber

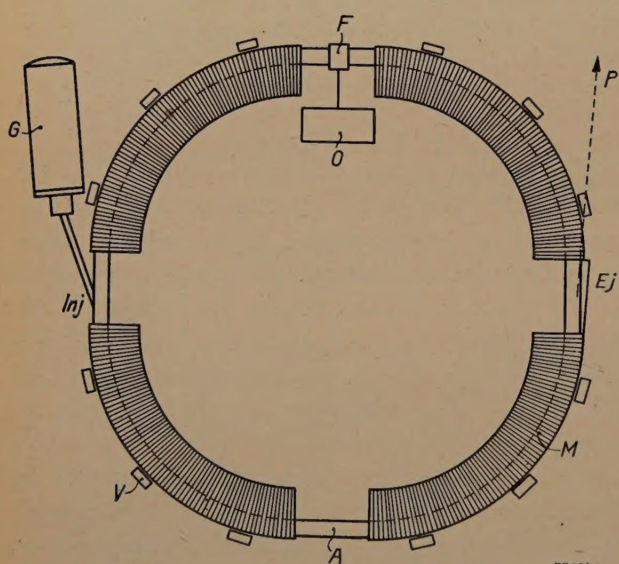



Fig. 1. Plan-view of the Cosmotron. The accelerated protons move on (or near) the axis of the annular evacuated chamber $A$, which has a diameter of about 60 feet. The protons are injected into the chamber at *Inj*, with an initial energy of 3.5 MeV, from a Van de Graaff high tension generator $G$. Four electromagnets $M$ keep the protons on their track. The acceleration of the protons occurs at $F$, where an alternating electric field, generated by the oscillator $O$, gives the protons a "kick", once per revolution. When the protons have acquired their final energy, they emerge in a beam $P$ from the annular chamber at the ejector *Ej*. $V$ represent a number of high vacuum pumps for the evacuation of the acceleration chamber.

while their energy and momentum is increasing, the magnetic field is increased continuously, up to a maximum value of 1.4 Wb/m$^2$. This value will allow the protons to be kept on their track with a final energy of 3100 MeV. The beam of accelerated protons can be ejected from the annular chamber by a suitable deflector device accommodated in another straight section of the chamber.

At the injection energy of 3.5 MeV, the proton velocity is $2.6 \times 10^7$ m/sec. As the path along the axis of the annular chamber has a total length of about 70 meters, the time for one revolution is initially about $^1/_{350\,000}$ second. This means that the accelerator section proper must carry an alternating electric field of frequency about 350 000 cycles/second, in order to give the circulating protons a "kick" each revolution in the correct phase. At a final energy of 3000 MeV, the proton velocity (for the calculation of which the relativistic formula must now be applied [2]) is approximately 10 times the initial value, so that during the course of the acceleration of a burst of protons the frequency of the accelerating electric field must be gradually increased from 0.35 to about 4 Mc/s.

Although this brief description would suffice for our further discussion of the accelerator, a few further details of the design study published by the Brookhaven group [1]) may be mentioned in this section for the sake of completeness. One of the major problems of the project was the supply of the large magnetic energy required for keeping the protons on their track. The field of 1.4 Wb/m$^2$ in a space 70 metres long and roughly $36'' \times 9.35''$ in cross-section (gross dimensions, as against the above-mentioned net dimensions inside the chamber) involves a magnetic energy of 12 megajoules. This formidable magnetic energy [3]) must be built up during the acceleration time of one burst of protons and taken away relatively quickly after the ejection in order to make the apparatus ready for the next burst. As it would be very uneconomical to dissipate the magnetic energy after each burst, it is stored mechanically in the form of the kinetic energy of a large flywheel and recycled. In order that the build-up of the magnetic energy may be accomplished with a reasonable peak power, and that the acceleration may be achieved with not-too-large "kicks", the acceleration time for one bunch of protons must be relatively long. An acceleration time of 1.0 sec was chosen. (This means that the protons will make roughly three million revolutions during their acceleration.) The cooling of the magnet and the available power of the motor-

[2]) A convenient graph for the general velocity-energy relationship may be found in Philips tech. Rev. **11**, p. 68, 1949.

[3]) For a comparison, the reader is referred to the description of the Amsterdam synchrocyclotron given in this Review **12**, 354, 1950: it was there mentioned that the large electromagnet contains a magnetic energy of 0.65 megajoules, whereas the magnetic energy in the gap of a high power loudspeaker amounts to about 0.25 joules.

generator coupled to the flywheel are such that the acceleration of a bunch of protons may be repeated every 5 seconds.

Another important problem was the simultaneous variation of the magnetic field and of the frequency of the accelerating electric field. Because of the essentially non-linear behaviour of an electromagnet as a circuit element, it would be difficult to realize an exactly predetermined increase of the magnetic field with time. The designers of the Cosmotron avoided this difficulty by regarding the magnetic field as the independent variable. The expected time-variation of the magnetic field (*fig. 3*) was derived from the circuit constants and model measurements. From the rate of change $dB/dt$ of the magnetic field it can be deduced by how much the momentum (and the energy) of the protons must increase after each revolution in order to keep them on the same orbit. This required energy gain per revolution is plotted against time in *fig. 4*; it is seen to decrease during the acceleration period from an initial value somewhat greater than 1000 eV to a final value of rather more than 600 eV per revolution. The velocity of the protons resulting at each instant of the acceleration time (and which depends only on the instantaneous value of $B$) determines the frequency that is required at that instant for the accelerating electric field; cf. curve $f$ in fig. 3. The problem of controlling the frequency to obtain this time variation with the required precision, was solved at Brookhaven in an elegant manner: the derivative of the magnetic field is measured continuously by means of a pick-up coil, and the integrated signal of this

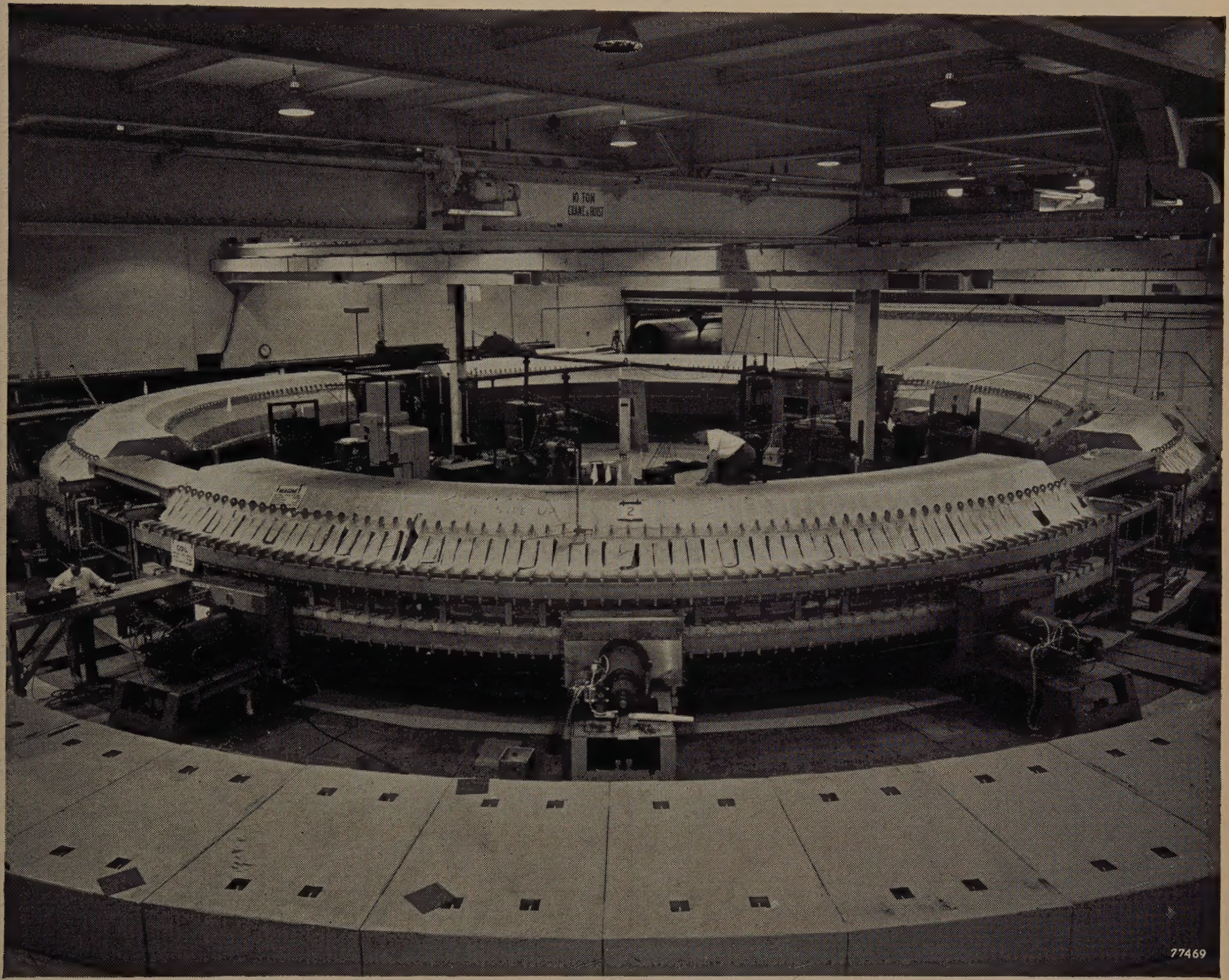



Fig. 2. General view of the Cosmotron, in the Brookhaven National Laboratory, U.S.A. The four large electromagnet quadrants, surrounding the four sections of the annular acceleration chamber, have a total weight of 2200 tons. In the background is the Van de Graaff generator placed in a horizontal tank. Farther to the right is the accelerator unit. The concrete wall seen in the foreground protects personnel from the radiation of the machine.

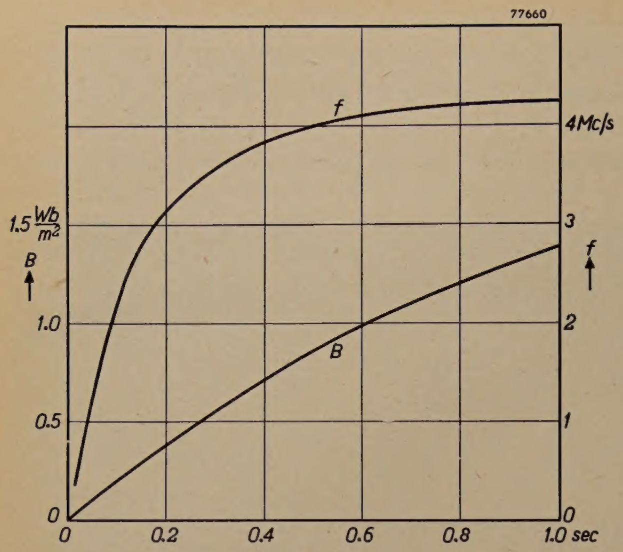



Fig. 3. Variation with time of the flux density $B$ of the magnetic field during one accelerating period. This field, which forces the protons to move in their circular orbit, is regarded as the independent variable: the frequency of the accelerating electric field must then vary according to the curve $f$, in order to ensure that the protons circulating at an increasing rate will remain on their track inside the annular chamber.

coil, is used for controlling the frequency of a "permeability-tuned" $LC$-oscillator producing the accelerating radio frequency field [4]). The tuned circuit of this oscillator employs an inductance containing a Ferroxcube III core with an initial permeability of about 1000. The control signal provides an increasing bias magnetization of the core, causing its effective permeability to drop sharply, thus decreasing the inductance. In this way the required wide frequency sweep (fig. 3) is obtained, together with the required frequency stability. A frequency error as small as 0.3% would cause the proton orbit radius to exceed the latitude allowed by the annular chamber. With the oscillator described, when the temperature of the Ferroxcube core is held constant to 0.1 °C, the oscillator frequency is stable and reproducible at any control signal value to better than 0.1%. The oscillation amplitude is held constant at a value such that the peak accelerating field is about twice the highest instantaneous value needed (see above).

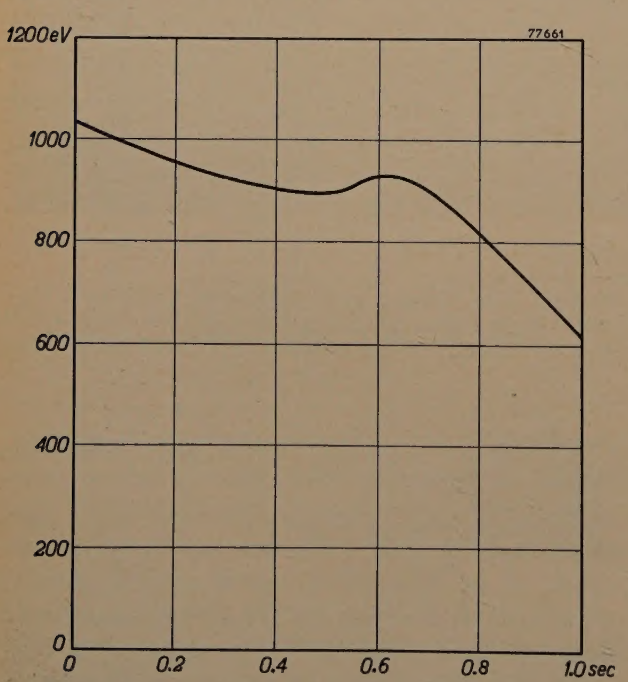



Fig. 4. Required energy gain per revolution of the protons as a function of time.

With a view to the phase stability of the revolving protons, these must pass through the alternating electric field at a certain phase angle $\Theta$ after its peak. If the protons are focussed to a bunch at a phase of about $\Theta=60°$, the peak value of the accelerating radio-frequency voltage must be about 2200 V. Matters of orbit stability, which of course were of prime importance in the design, need not be considered here, though in the last section they will have to be mentioned.

A Ferroxcube core is thus encountered in the tuning circuit of the oscillator, at the heart of the Cosmotron. This small core, however, did not offer any specific manufacturing problems and need not be discussed in this article. The Ferroxcube core forming the subject of this article is also part of the radio-frequency accelerating device, but serves the purpose of *transferring* the radio-frequency energy to the proton beam.

## The accelerating unit

The manner in which the longitudinal radio-frequency electric field is established in the acceleration path of the protons is one of the unique features of the Cosmotron as compared with other types of particle accelerators. The method [5]) may be roughly described by regarding the large circular path of the protons as the single turn secondary winding of a transformer, whose primary winding consists of a coil (having one or more turns) in the anode circuit of a power amplifier (*fig. 5*) driven by the radio-frequency oscillator. Both windings are effectively coupled by a ferromagnetic core (*fig. 6*).

The Brookhaven workers were able to consider the adoption of this novel system because, at the time that the design work on the Cosmotron had begun, the development at the Philips Laboratories

[4]) A. I. Pressman and J. P. Blewett, A 300 to 4000 kilocycle electrically tuned oscillator, Proc. Inst. Rad. Eng. **39**, 74-77, 1951.

[5]) A proposal to accelerate particles by a method along these lines was already made by A. Bouwers, in his book: Elektrische Höchstspannungen, J. Springer, Berlin 1939, p. 83.

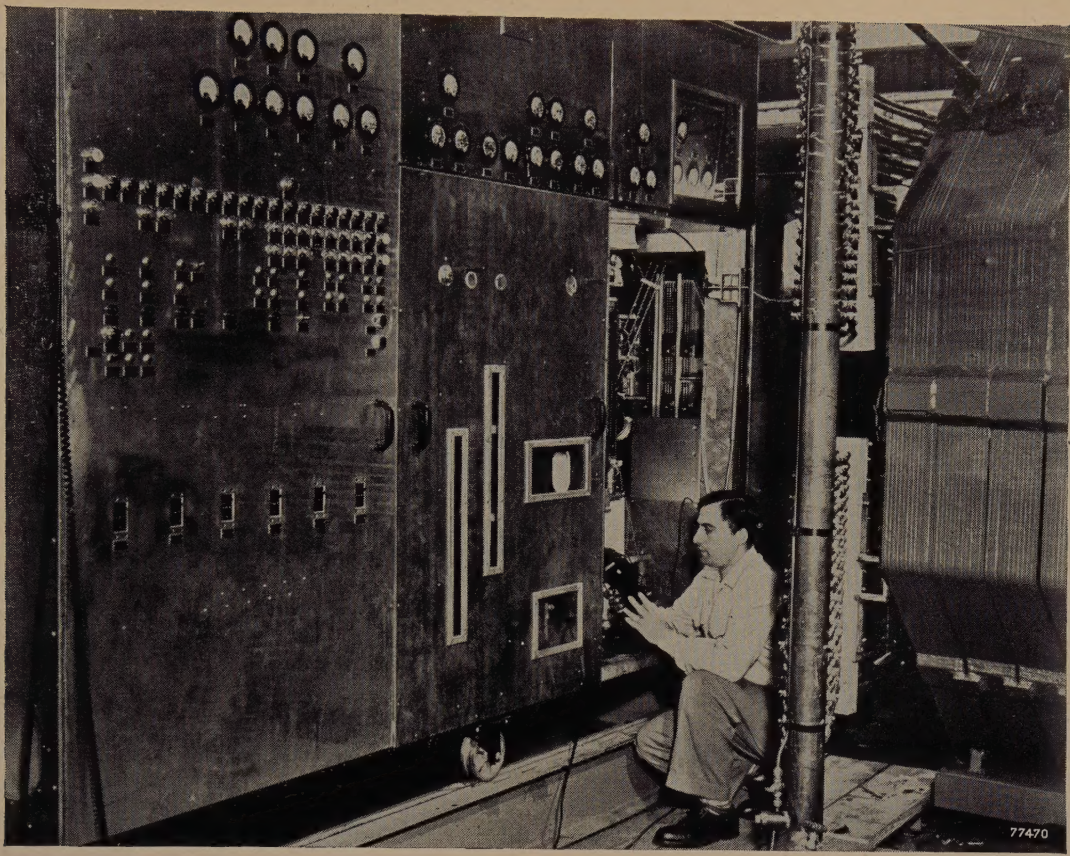



Fig. 5. Power amplifier supplying the radio-frequency energy to the primary of the transformer.

at Eindhoven of ferromagnetic materials suitable for very high frequencies had become known [6]). The usual transformer steel, even with extremely fine lamination, would not do in this case because of excessive eddy current losses. Powdered cores of iron or of "Permalloy" also offered no satisfactory prospects (see below). The new materials, however, owing to their very high resistivity, could be expected to be adequate even with sections several centimeters in thickness.

Quantitatively, the conditions imposed on the core material were derived from the formula for the input impedance $Z$ of the above-mentioned transformer (cf. the first article quoted in [1]), eq. 17). This formula in simplified form says that $Z$ is proportional to

$$f\mu_r\left(\frac{1}{Q}+\mathrm{j}\right),$$

$f$ being the frequency, $\mu_r$ the relative permeability of the core material and $Q$ the usual figure of merit of the primary winding including the effects of core losses. In order to obtain the desired accelerating voltage (2200 V peak) with a reasonable anode current of the oscillator, a high impedance $Z$ is desired, while for reducing power loss and heat dissipation in the transformer, the real component of $Z$ should, of

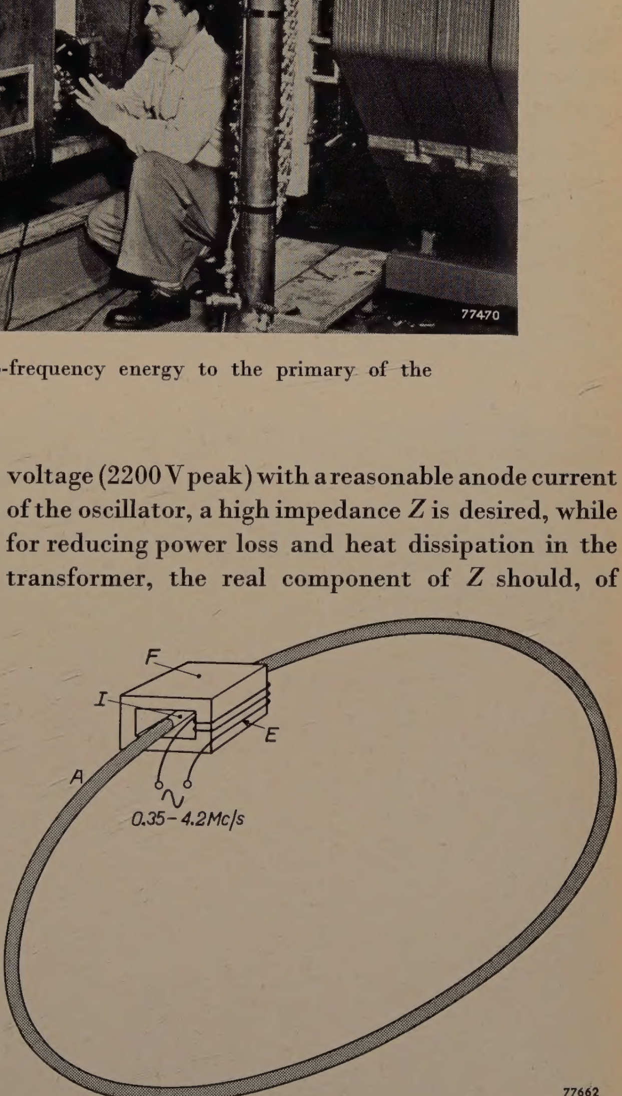



Fig. 6. Simplified representation of the acceleration system of the Cosmotron. The metallic annular acceleration chamber $A$ constitutes the secondary winding of a transformer with primary winding $E$ and ferromagnetic core $F$. $I$ is an insulating section of the annular chamber, across which the accelerating voltage is produced. — In reality the core $F$ is enclosed in a copper shield having the gap $I$ in the centre. The shield forms an autotransformer with the windings. Thus the electric field is restricted to the gap and radio interference prevented.

[6]) J. L. Snoek, Non-metallic magnetic materials for high frequencies, Philips tech. Rev. 8, 353-360, 1946; J. L. Snoek, New developments in ferromagnetic materials, Elsevier Publishing Co., Amsterdam 1947.

course, not be too large. A core material with a high permeability $\mu_r$, preferably not less than 500, and low losses resulting in a reasonably high value of $Q$, say, not less than 0.5 even at the highest frequency used (4.2 Mc/s), was therefore desirable. Comparative measurements of $\mu_r$ and $Q$ for ring core samples of several materials were performed by the Brookhaven group. Their results [1]), shown in *table I*, clearly pointed to the superiority of the ferrite material for this application, though they did not yet conclusively demonstrate that ferrites could do the job.

It should be emphasised that the system outlined in fig. 6 was not the only practicable solution for the problem of transferring energy to the proton beam from a radio frequency source. An alternative solution considered by the Brookhaven group involved the use of a *tuned* system, for example a resonant cavity, driven at a varying frequency and continuously tuned over the desired frequency sweep. Although the first system was chosen for the Cosmotron, the alternative system has gained new interest, as it will probably be used in a new type of accelerator which can yield even higher particle energies and which is now the subject of study by a number of groups including that at Brookhaven. We shall return to this further development at the end of this article.

**Table I.** Properties of magnetic core materials at 1 megacycle, as measured by the Brookhaven group [1]).

| Material | $\mu_r$ | $Q$ |
|---|---|---|
| 4-79 Mo Permalloy (0.001″ laminations) | 600 | 0.6 |
| Fe powder (80 mesh grade B) | 35 | 2.0 |
| 81 Permalloy powder (120 mesh) | 75 | 1.6 |
| 2-81 Mo Permalloy powder (120 mesh) | 125 | 3.0 |
| Typical ferrite | 1000 | 6.0 |

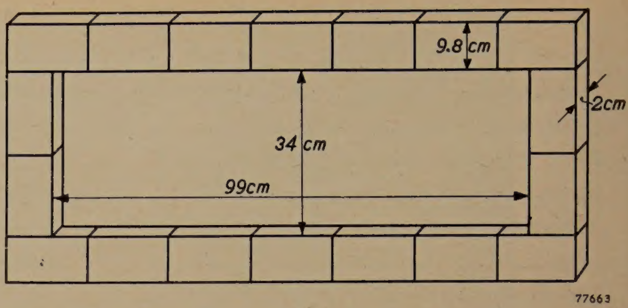



Fig. 7. Dimensions of one of the 24 "picture-frames", made of bricks of Ferroxcube IV, manufactured by Philips for the core of the Cosmotron.

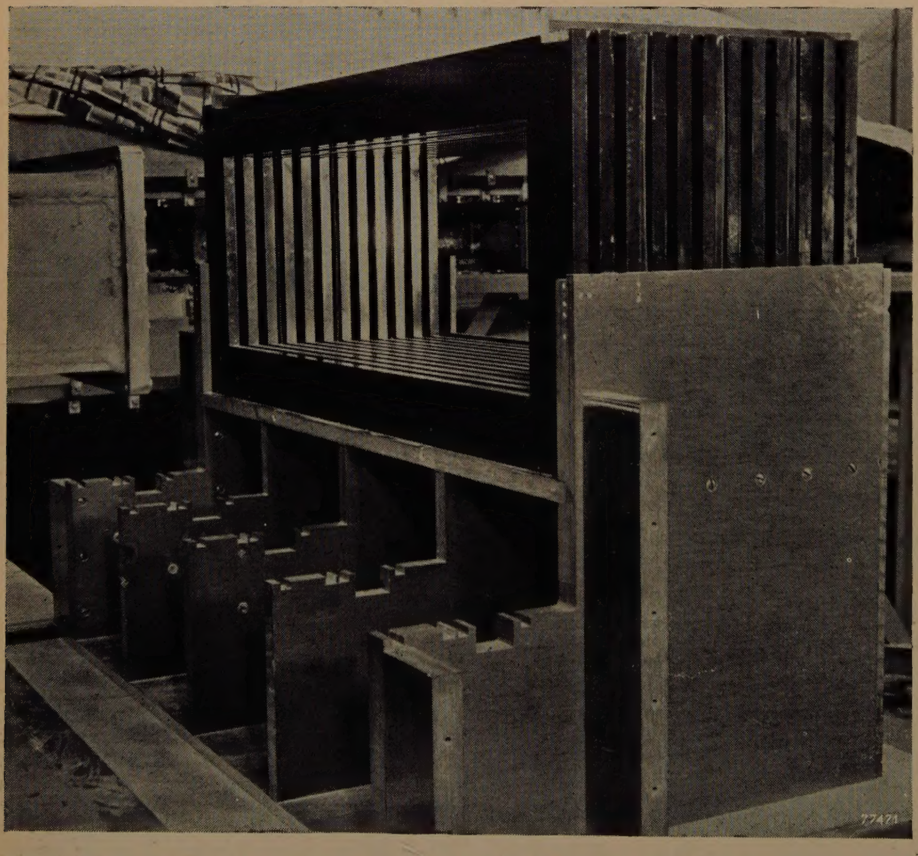


Fig. 8. Bank of 12 Ferroxcube "picture-frames", during the assembly of the core of the Cosmotron. On the left, part of the annular acceleration chamber, which runs through the "window" of the core, can be seen.

The adoption of the transformer system presented the makers of ferrites with two practical problems: the choice of the ferrite material best suited for the purpose, and the actual manufacturing of the large core structure. The "window" of the core must be about 100 cm wide and 34 cm high, to allow space for the annular vacuum chamber and the primary winding. In order to keep the magnetic flux density sufficiently low, a core cross-section of 10 × 50 cm was required. This would mean a total weight of the ferrite core of about 750 kg.

In 1948 the Brookhaven group consulted the Philips Laboratories, Irvington, regarding a suitable fer-

rite for the core structure. After the characteristics of different materials for the purpose were investigated, part of the final core was assigned to Philips in November 1949. This part consisted of 24 "picture frames" of Ferroxcube IV, of the size shown in *fig. 7* and composed of bricks with dimensions 170.0 × 98.0 × 20.0 mm. The delivery of the whole batch was completed in May 1950. The frames were installed in the Cosmotron in two banks of 12 each. The photograph in *fig. 8*, made during the course of the assembly of the Cosmotron, shows one of these banks.

A few details of the preliminary investigations and of the manufacturing method will now be given.

**Choice of material and manufacturing of the Ferroxcube frames**

The ferrite chiefly manufactured at the time was Ferroxcube III, a solid solution of manganese-, zinc- and ferrous ferrites. This type of ferrite has by far the lowest hysteresis losses, a property of great importance for telephone applications, and in fact, the use of ferrite in carrier telephony was then commercially the most important [7]). The different varieties of Ferroxcube III have initial permeabilities [8]) varying from 800 to 1700, resistivities of the order of 100 ohm cm (a factor of 10 million times greater than that of iron) and they yield $Q$-values of 10 at frequencies up to 0.3 to 0.8 Mc/s. From the latter property, it was estimated that core sections with a thickness of a few centimeters would not introduce excessive eddy-current losses. This conclusion appeared to be verified by tests performed on samples of the material of the small size usual in carrier telephony and other applications. When, however, bricks of this material having dimensions of several cm and suitable for the assembling of a test core for the Cosmotron were made at Eindhoven and tested at Brookhaven, it was discovered that their initial permeability $\mu_i$ decreased abnormally rapidly with increasing frequency resulting in a very low value at about 2 Mc/s (*fig. 9*). Closer investigation of this unexpected phenomenon at Irvington revealed the existence of a *dimensional effect,* which could be shown to be due to the material possessing a very high dielectric constant [9]).

[7]) G. H. Bast, D. Goedhart and J. F. Schouten, A 48-channel carrier telephone system, Philips tech. Rev. **9**, 161-170, 1947 and **10**, 353-362, 1948/49.

[8]) Cf., for example, J. J. Went and E. W. Gorter, The magnetic and electrical properties of Ferroxcube materials, Philips tech. Rev. **13**, 181-193, January 1952.

[9]) F. G. Brockman, P. H. Dowling and W. G. Steneck, Dimensional effects resulting from a high dielectric constant found in a ferromagnetic ferrite, Phys. Rev. **77**, 85-93, 1950.

The rapid decrease of $\mu_i$, which could be interpreted, in general, as a resonance effect, was shown to shift to higher frequencies when air gaps were introduced into the core, an increasing air gap with a given frequency thus giving rise to a larger effective permeability (*fig. 10*). This result made it very probable that the permeability observed with no air gap was not a true constant of the material. Further evidence for this was obtained from experiments with laminated cores. Again, the apparent resonance effect was shifted to higher frequencies as the core was subdivided more and more in a direction perpendicular to the magnetic flux (*fig. 11*). Since the effect of ohmic eddy currents certainly could not

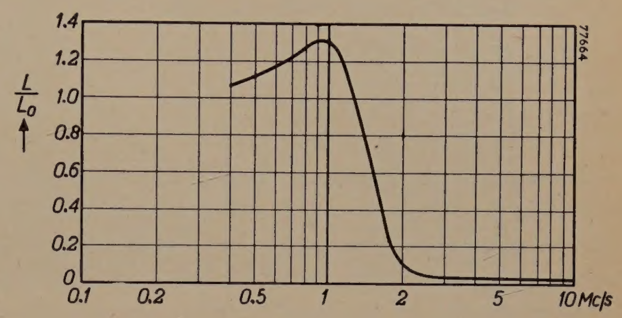



Fig. 9. The permeability of Ferroxcube III, measured on the sample bricks, for the Cosmotron core, plotted against frequency. The ratio of the self-inductance $L$ of a ring-coil with a core of these bricks to that of the same coil at low frequencies $L_0$, is used as a measure of the permeability.

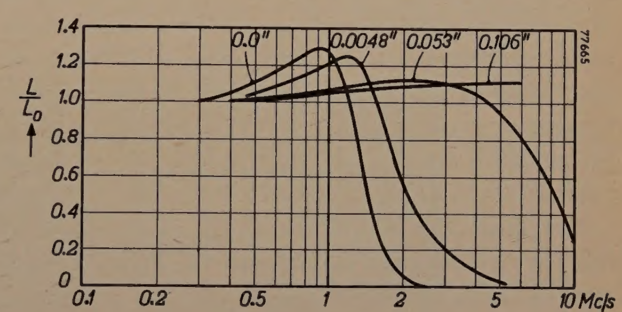



Fig. 10. Same as in fig. 9, with air gaps in the core of 0, 0.12, 1.35 and 2.7 mm respectively. The sharp drop in permeability occurs at higher frequencies as the air gaps get larger.

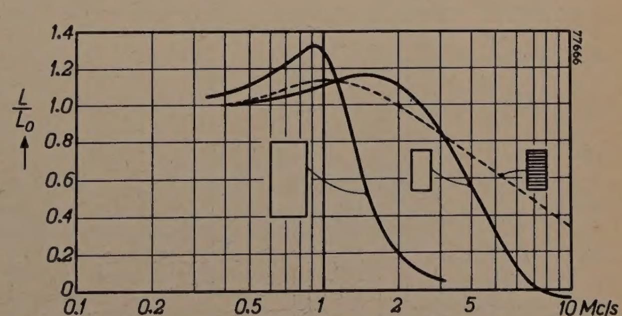



Fig. 11. Same as fig. 9, for cores of different cross-sections and subdivided into laminations as shown. The smaller the dimensions, the higher the frequencies at which the decrease occurs. (In one of the curves, negative values of $L$ are seen to occur; this means that a dimensional resonance frequency has been passed and that the induction in the core then is oscillating in antiphase with the exciting alternating field.)

account for the results, one was led to consider the dielectric properties, and a relative dielectric constant $\varepsilon_r$ of quite a surprising value was found, being as high as 50 000. The phenomena observed could then be explained by the superposition upon the usual eddy currents due to ohmic conduction of another type of eddy current which flows by dielectric displacement. Such currents will be out of phase with the ohmic eddy currents, and they can lead to a dimensional resonance in an inductor wound on a core of large enough cross-section. The wavelength of an electromagnetic wave in such a material is given approximately by:

$$\lambda \approx \frac{c}{f} \cdot \frac{1}{\sqrt{\mu_r \varepsilon_r}} \qquad (c = \text{velocity of light in vacuo}).$$

Standing wave effects can be noted when the smaller dimension of a core, perpendicular to the magnetic flux, is $^1/_2$ wavelength.

Interesting though this discovery was from a scientific point of view, it showed that Ferroxcube III would not be a suitable material for the Cosmotron core. However, another type of ferrite, Ferroxcube IV (nickel zinc ferrite), was available at Eindhoven, and a variety of this type met the specifications in a satisfactory manner. This material has a sufficiently small dielectric constant and a much higher resistivity than Ferroxcube III (of the order of $10^6$-$10^7$ ohm cm), so that no dimensional resonance effects could occur at the frequencies to be used, even with bricks of large dimensions. Consequently, the frames for the Cosmotron were made from Ferroxcube IV. The permeability versus frequency curve of one large lamination is shown in *fig. 12.*

The large size of the core structure, which in this way influenced the choice of the material, also created some difficult manufacturing problems. Ferrite materials are prepared by *ceramic* methods, i.e. the powdered materials, after the addition of suitable binders, are given the shape of the objects to be manufactured by pressing, extruding or the like, the shaped parts then being dried and fired at a high temperature. During the firing a shrinkage occurs, which in the case of ferrites may amount to 20-24% (on the linear dimensions). This large shrinkage, which is illustrated by *fig. 13,* imposes very strict requirements on the uniformity of temperature during drying and firing of large bricks such as were required for the Cosmotron core, in order to avoid cracks. The bricks were moulded in an 80 ton press and then dried very slowly, remaining for several days in a large drying chamber at about 40 °C. The firing was then performed in special ovens in an oxygen atmosphere, with a temperature cycle covering a period of several days. Such an oven is shown in *fig. 14.* The firing process, of course, must be conducted very carefully, as the reactions occurring during firing are essential for the development of the special magnetic properties of a ferrite.

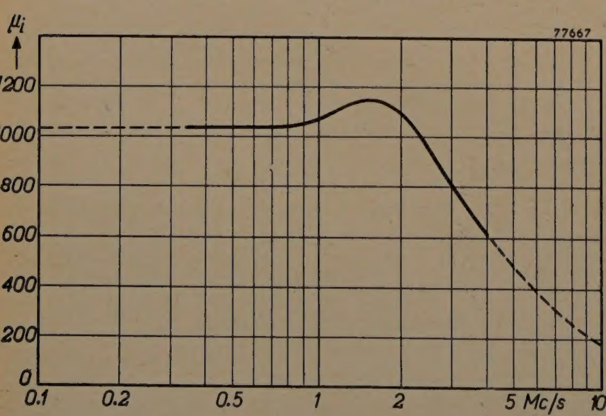



Fig. 12. Relative initial permeability $\mu_i$ of Ferroxcube IV, measured on one of the picture frames for the Cosmotron, plotted against frequency. A decrease is seen to occur at much higher frequencies than in the case of Ferroxcube III.


Fig. 13. A brick of Ferroxcube, before and after firing. During the firing at high temperature a shrinkage of 20-24% on linear dimensions occurs.

The bricks then had to be cemented together to form the "picture frames" as outlined in fig. 7. The unavoidable air gaps between adjacent bricks were reduced to a few microns by grinding the faces of the bricks with this precision; it will be appreciated that severe requirements were imposed on the rectangularity of the bricks, the permissible deviation of the 90° angle amounting to 1′ of arc in the largest surface of the brick and 1′30″ in the second largest.

It was established at Eindhoven that a plastic of the aethoxyline group, hardening at a temperature of about 180 °C, would be a suitable cement for ferrite materials. Experience with a sample picture

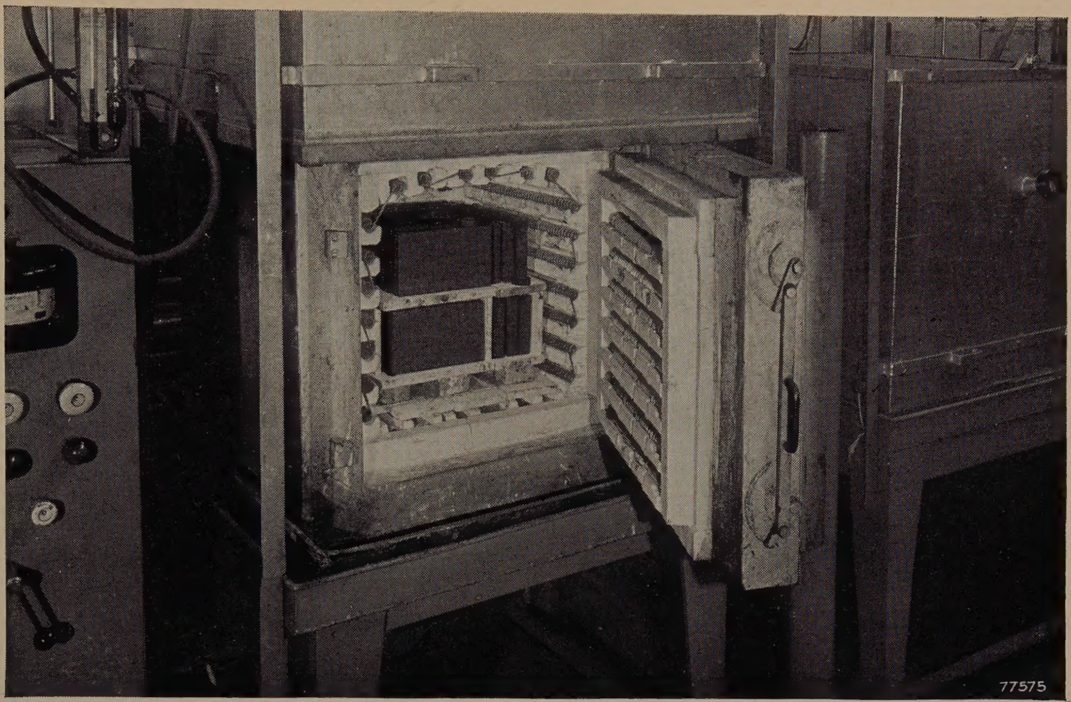



Fig. 14. One of the electric ovens in which the Ferroxcube IV bricks for the Cosmotron core were fired.

frame, used for preliminary measurements, had shown however, that the simple cementing and baking procedures applied to similar joints of other materials and also of Ferroxcube III were not satisfactory in the case of Ferroxcube IV. This could be ascribed to the *porosity* of the sintered Ferroxcube IV material, a property essential for giving the oxygen gas access to the innermost parts of the sample during firing, but unfortunately also giving water vapour, entering from the sides, access to the thin plastic films in the joint, causing deterioration in a few months.

A special procedure was therefore developed for the cementing of the Ferroxcube IV bricks. The main steps of this procedure involved a thorough cleansing of the surfaces to be cemented, a repeated impregnation in vacuo with the plastic cement and baking of the bricks. In the cementing

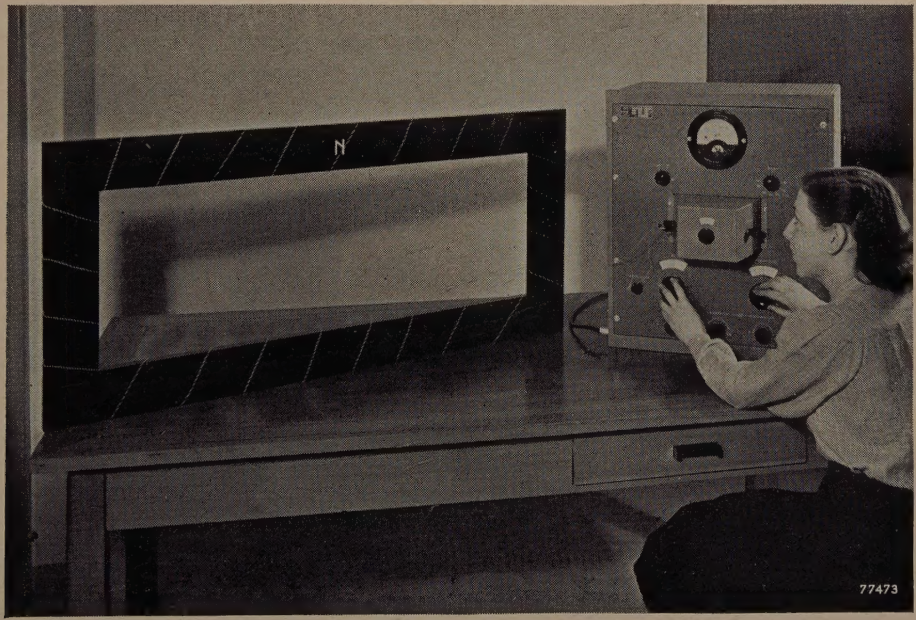



Fig. 15. One of the "picture-frames" for the Cosmotron core, during control measurements in the Ceramic Factory at Eindhoven.

process, a special tool enabled the bricks of a frame to be pressed together by a constant force during baking, so that most of the plastic layer applied between adjacent bricks is driven out of the joints during that part of the polymerization period when the viscosity is lowest. In this way the gap lengths

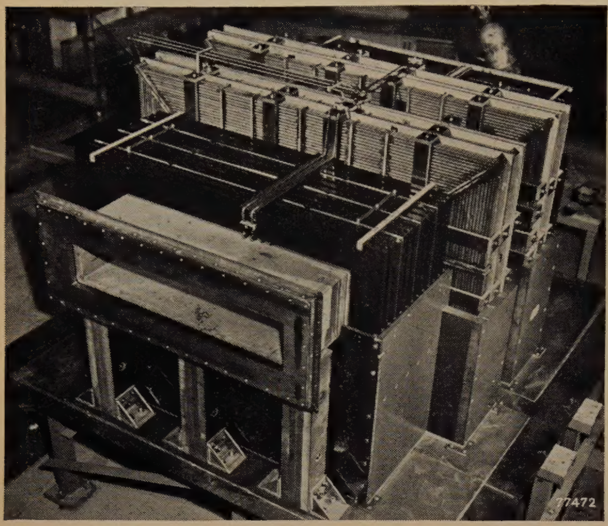


Fig. 16. The completed ferrite core of the Cosmotron, assembled in position. The Ferroxcube "picture frames" are seen in the centre and in the background of the photograph.

of non-ferromagnetic material were reduced to the small dimensions mentioned above. As a final precaution, the cemented frames were coated with a water repellent polyvinyl lacquer.

The breaking strength of the joints obtained is considerably larger than that of the Ferroxcube IV slabs themselves. This had been established by experiments, and it was proved again in shipping the frames to Brookhaven: when a box containing one of them was dropped from the hoisting crane, the frame was broken at two places, but not at any of the joints.

The photograph *fig. 15* shows one of the completed frames in the course of testing at Eindhoven. *Fig. 16* is a photograph of the complete core, assembled at Brookhaven and containing the two banks of picture frames.

Operation of the completed core under the load conditions imposed at Brookhaven has been reported to be completely satisfactory. The frames are separated by air spaces, and since the core is surrounded by a copper shield, forced air cooling can be applied. Even uncooled, however, the core functions without appreciable temperature rise. For further information about the performance of the oscillator and accelerator unit as a whole, the reader should refer to the recent publication by the Brookhaven group [1]).

**The application of ferrites in "strong-focusing" accelerators**

Since the Cosmotron was put into operation great interest has been aroused by the discovery by members and consultants of the Brookhaven group of the so-called "strong-focusing" principle [10]). Without entering into a detailed discussion, it may be said that a new method of reducing the amplitudes of radial and vertical oscillations of the revolving particles will allow the cross-section of the annular vacuum chamber to be reduced considerably, compared with the cross-section of the Cosmotron. Thus, with about the same magnetic energy — and therefore, very roughly, with a total cost of the same order — particles could be kept on a circular track with a diameter, say about 10 times that of the Cosmotron. In this way a particle energy of about 10 times that of the Cosmotron, i.e., of about 30 000 MeV, could be obtained (the momentum according to eq. (1) is proportional to the product $BR$, and at these high energies the energy is approximately proportional to the momentum; see also the graph of fig. 10 in the article quoted in [2]).

Plans for accelerators using this principle are actually being studied at several places. Such an accelerator would not make use of a single accelerating unit like that of the Cosmotron, but it would contain a large number of accelerating units, based on the continuously tuned resonator principle mentioned above as an alternative possibility. No

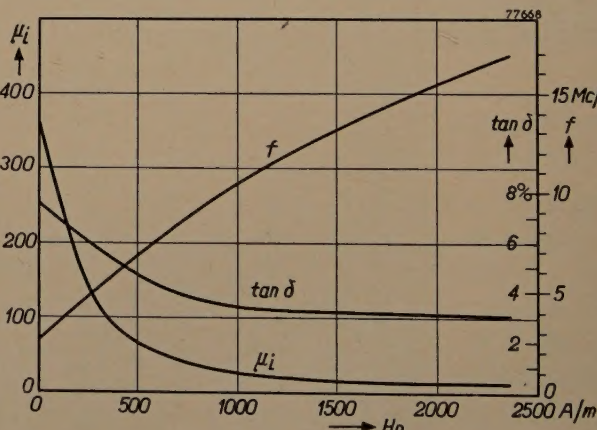



Fig. 17. A Ferroxcube material suitable for accelerators employing tuned resonant cavities has been developed at Eindhoven. The permeability $\mu_i$ of this material is varied by means of a polarizing field $H_p$ and the curve $f$ shows the frequency variation obtainable in this way (1 : 6). The figure of merit $Q$ ($= 1/\tan \delta$) of a cavity filled with this material is greater than 10 even at the lowest frequencies.

[10]) E. D. Courant, M. S. Livingston and H. S. Snyder, The strong-focusing synchrotron — a new high energy accelerator, Phys. Rev. **88**, 1190-1196, 1 Dec. 1952.

transformer then would be needed, but oddly enough, ferrites again would have to be employed, on an even larger scale than in the Cosmotron: the resonators would be resonant cavities, containing massive cores of ferrite. The resonant frequency of such a cavity can be changed by a saturating magnetic bias field, much in the same way as in the master oscillator of the Cosmotron described above. As several tons of ferrite would go into each cavity, a total quantity of several hundred tons would be needed for a 30 000 MeV accelerator! The ferrite to be used will have to meet very exacting requirements. One of the tentative designs calls for a lowest resonant frequency of 3 Mc/s and an upper limit of 17 Mc/s. This frequency sweep (about 1 : 6) implies a corresponding permeability change of 1 : 36, to be obtained by applying a polarizing magnetic field. Another requirement is a $Q$ at all frequencies of interest of 10 or more, at a maximum flux density at the lower frequency limit of 0.01 $Wb/m^2$. In co-operation with the Brookhaven group, the Philips Laboratories at Eindhoven have developed a ferrite which satisfies these requirements, as is illustrated by *fig. 17*. Samples of this ferrite are now under test at two laboratories associated with the high energy accelerator design.

**Summary.** The Cosmotron proton accelerator, designed and built by the Brookhaven National Laboratory, U.S.A., has already delivered a beam of protons with an energy of 2300 million electron volts and is expected to yield protons of 3000 MeV. The accelerator unit of this machine consists of a large "transformer", the ferromagnetic core of which is excited by an alternating current whose frequency during the acceleration period of one second varies from 0.35 Mc/s to 4.2 Mc/s. At these high frequencies only ferrite materials, which have very low eddy-current losses, could be used for the core. The major part of the ferrite core was manufactured by Philips at Eindhoven after a suitable variety of Ferroxcube meeting the permeability and figure of merit requirements had been selected by the Brookhaven Laboratory in co-operation with the Philips Laboratories at Irvington, U.S.A., and at Eindhoven. Some glimpses of the problems encountered in the manufacture of the Ferroxcube core are given in this article. Mention is also made of the development at Eindhoven of another variety of Ferroxcube which will be suitable for the accelerator units of machines based on the principle of "strong focussing", which are expected to yield particles of energies of 30 000 MeV or more.

# THE PRINCIPLE OF THE MAGNETIC RECORDING AND REPRODUCTION OF SOUND

by W. K. WESTMIJZE.

621.395.625.3

*The hysteresis and non-linear character of ferromagnetism would appear to render the magnetic recording of sound a hopeless task. Despite these difficulties, sufficiently faithful recordings on ferromagnetic tape were accomplished as early as 1907 by pre-magnetizing the tape. Nowadays, the same result is obtained by superimposing an HF alternating current on the signal current. For a correct application of this principle, a careful study of the magnetization process of a magnetic tape is required. Such an investigation is described here, covering the recording and reproduction processes themselves, the frequency characteristic, distortion, noise, and other phenomena which influence the quality of the reproduction. The conclusion from this work is that magnetic recording not only competes successfully with other sound-recording methods, but may even surpass them.*

## Introduction

The nature of the processes involved in the recording and reproduction of sound on a ferromagnetic tape will first be discussed. The apparatus (*fig. 1*) and some properties of the ferric oxide coated magnetic tape have been discussed in an earlier publication [1]). It was there pointed out that the material of the tape should have a certain remanence and not too low a coercive force, and consequently must show a certain degree of hysteresis. Special measures are then necessary to ensure linearity, i.e. to ensure that the resultant of two or more superimposed signals will be solely the sum of these signals.

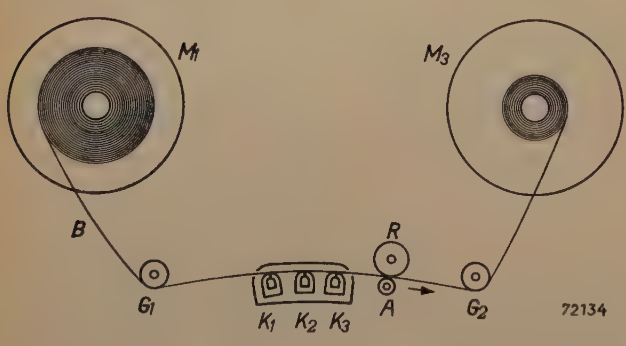



Fig. 1. Schematic representation of a tape-recorder. $M_1$ supply reel, $M_3$ take-up reel, $B$ magnetic tape, $K_1$, $K_2$, $K_3$ erasing, recording and reproducing heads. $A$ drive capstan, $R$ rubber pressure idler, $G_1$ and $G_2$ idlers.

The process of magnetization as it occurs in the material of the tape will first be examined with the aid of a schematic representation. Next, the recording and erasing of signals will be discussed. Other matters to be dealt with include distortion (non-linearity between magnetization and signal strength), the reproduction process, the frequency characteristic, noise and the "print" effect.

Finally, the merits of the magnetic recording process will be compared with those of other methods of recording sound.

## Schematic representation of the magnetizing process

As a rule, when working with ferromagnetic substances, a distinction should be made between reversible processes (in which the magnetization [2]) closely follows the field intensity), and irreversible processes. With small variations in the intensity of the external field, the magnetization is practically reversible. Irreversible changes occur when the variation in the field intensity exceeds a certain limit. Localised sudden changes — Barkhausen

[1]) D. A. Snel, Magnetic sound recording equipment, Philips tech. Rev. **14**, 181-190, 1953 No. 7; hereafter referred to as I.

[2]) In a material uniformly magnetized by a solenoid, the induction $B$ is composed of two parts:

$$B = \mu_0 H + J.$$

In this $\mu_0 H$ represents the contribution of the magnetic field of the current and $J$ (the magnetization, i.e. the magnetic moment per unit of volume; $J = \mu_0 M$) the contribution of the material ($B$ and $J$ measured in Wb/m², $H$ and $M$ in A/m). The same formula is valid at every point of a piece of material of any given form, whether or not it has been placed in a magnetic field:

$$\mathbf{B} = \mu_0 \mathbf{H} + \mathbf{J},$$

where **B**, **H** and **J** represent, respectively, the induction vector, the field vector and the magnetization vector, at any point in the field. In general the magnetic *field* is built up from various contributing elements:

$$\mathbf{H} = \mathbf{H}_u + \mathbf{H}_m,$$

$\mathbf{H}_u$ representing the external field, originating in electric currents or other magnets, and $\mathbf{H}_m$ the field of the "magnet poles", which, due to the magnetization, occur on the surface and at discontinuities in the material.
In the case of a toroid $\mathbf{H}_m = 0$. In other cases, $\mathbf{H}_m$ and **J** are usually in opposite directions and, since a decrease of $\mu_0\mathbf{H}$ gives a greater decrease of **B**, the magnetization **J** will be smaller than it would be if $\mathbf{H}_u$ only were active. This is known as *demagnetization*. It should be borne in mind that the induction lines are always closed lines, as the induction **B** is subject to the law.

$$\operatorname{div} \mathbf{B} = 0.$$

jumps — then occur in the various domains. When the field intensity changes in the opposite direction the magnetic processes will again be at first reversible and then irreversible. In general, the critical

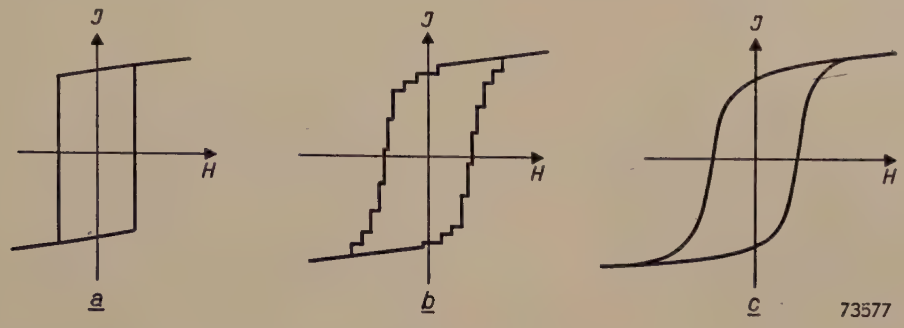



Fig. 2. Idealized and actual magnetization curves: (a) shows the curve for a particle magnetizable only in a positive or negative direction, (b) the superimposing of a small number of these curves, and (c) the same for an infinite number of particles.

field intensity will have different values for various elementary domains of the material. The resultant hysteresis loop (figs 2*b* and *c*) is obtained by superposition of the magnetization curves of the various domains (*fig. 2a*). This complicated behaviour may be represented [3]) by the idealised magneti-

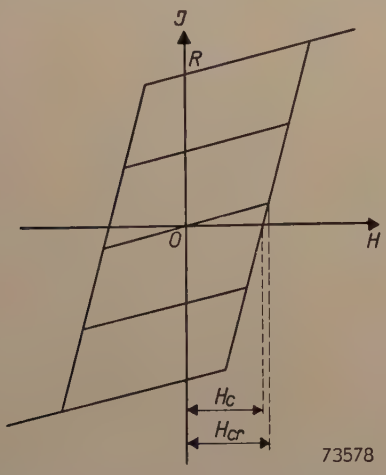



Fig. 3. Schematic magnetization curve, built up of two steep irreversible branches, connected by less steep reversible branches. The origin $O$ represents the non-magnetic state, $R$ represents the maximum remanence at zero field strength. $H_c$ represents the coercive force, $H_{cr}$ the critical field strength at which the magnetization becomes irreversible.

zation curves of figure 3, which are built up of two fixed irreversible branches, connected by two (less steep) reversible branches. The slope of the latter corresponds to the initial permeability (*fig. 3*).

Comparison with *fig. 4* shows that the real magnetization curve possesses the same character, apart from the rounding off of the sharp edges.

**Recording method**

In the magnetic recording of sound, the tape — consisting of a homogeneous magnetic material or a carrier coated with magnetic material — is passed across the gap of the recording head (*fig. 5*). This consists essentially of an electro-magnet, the magnetic field of which, within certain limits, may be assumed to be proportional to the energizing current. The latter is derived from the original signal via an amplifier.

The intensity of the magnetic field of a "ring-shaped" recording head is at its peak value in the gap, where, however, it cannot be used. The active portion of the field is the *stray* field, in the vicinity of the gap. It decreases rapidly in intensity in the lengthwise direction of the tape and in a direction perpendicular to the tape (i.e. the direction of the thickness). If, for example, the recording gap has a length [4]) of 10 μ, it may be assumed that the


*a* *b* *c*

Fig. 4. Actual magnetization curve, which, by means of an integrating circuit is displayed on a cathode-ray tube and photographed. Curve *a* is obtained by using an alternating current with a gradually decreasing field intensity, curves *b* and *c* by superimposing an alternating current with a higher frequency and a small amplitude on a given alternating current. It is clear, particularly from *c*, that irreversible processes also occur on the reversible portions, which for reasons of simplicity were neglected in the idealised magnetization curve. The scale of representation differs for the three figures.

[3]) A similar procedure was followed by H. Toomin and D. Wildfeuer (Proc. Inst. Rad. Engrs. **32**, 664, 1944).

[4]) The "length" of the gap in this type of recording head is defined from the lengthwise direction of the tape. The "width" of the gap corresponds to the width of the tape.

effective field extends only some tens of microns from the gap. Consequently, when using a homogeneous tape of thickness say, 60 μ, only a layer of about 15 μ facing the head will be magnetized.

Starting with a demagnetized tape, no permanent magnetization will be imparted to it unless the field strength of the applied signals is greater than a certain critical value $H_{cr}$. This may be seen


Fig. 5. Recording head. *a*) A core of laminated soft iron (*K*) with a very short air gap (*S*) is magnetized by a current flowing through winding (*W*). This creates a stray field (dotted lines) around the gap. The tape (*B*) is carried across this gap and every particle traverses this stray field, the intensity of which increases when approaching the gap and decreases after passing the gap.
*b*) enlarged drawing of gap with tape.

For a coated tape, there is therefore no point in making the coating thicker than 15 μ.

When a particle of the magnetic material moves past the recording head, it is exposed to a magnetic field varying from point to point as regards intensity and direction; in general it will also vary with respect to time. For simplicity, we will first confine ourselves to the case where the frequencies of the signal are so low that during the time that a particle is exposed to the active field, the signal field is independent of time. With a tape speed of 0.7 m/sec and an active area of 50 μ, giving a transport time of about $10^{-4}$ sec, this condition will be satisfied when the frequencies are lower than 1000 c/s.

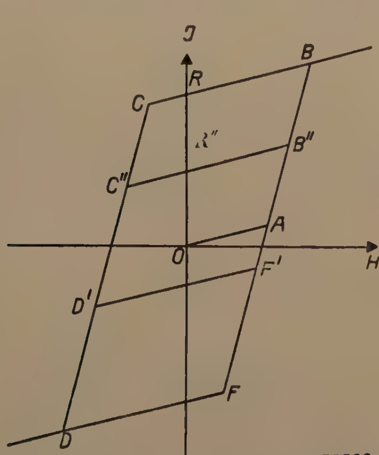



Fig. 6. If the material is exposed to a strong field which first increases and then decreases, the reversible portion *OA* is first described and then the loop *BCDF*. If now the field starts to decrease when the point *B''* is reached, then *B''C''* is described. A similar effect is obtained for a negative field after it has reached its largest value, say, at *D'* (line *D'F'*).

from the schematic magnetization curve of fig. 3. (In fact, there will be a very small remanent magnetization.) Only when the peaks of the signal

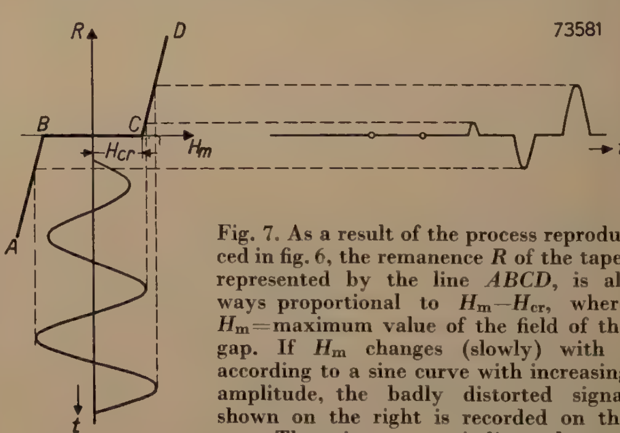



Fig. 7. As a result of the process reproduced in fig. 6, the remanence *R* of the tape, represented by the line *ABCD*, is always proportional to $H_m - H_{cr}$, where $H_m$ = maximum value of the field of the gap. If $H_m$ changes (slowly) with *t* according to a sine curve with increasing amplitude, the badly distorted signal shown on the right is recorded on the tape. The points —o—o— indicate the non-recorded peaks.

field exceed the critical value $H_{cr}$ will the magnetization change, say, from *O* via *A* to *B''* (*fig. 6*), and from there fall back to *R''*, rendering the tape permanently magnetized. Evidently the remanence *OR''* is not now proportional to the value *H* of the signal field, but to $H - H_{cr}$, with the result that the signal is badly distorted.

The result of the recording of a sinusoidal signal of a low frequency and gradually increasing amplitude would be as represented in *fig. 7*.

Of course, the distortion could be diminished by the use of a material with a lower coercive force. However, as pointed out in article I, a certain coercive force is needed to prevent distortion of the

sound track by stray fields and to counteract the influence of demagnetization in regions of sharp changes in the magnetization (i.e. small wavelength, corresponding to high frequency).

One solution of the linearity problem which has been used from the early days of magnetic recording[5]) is as follows. Before the tape is carried past the recording head, it is exposed to a direct field of such intensity that it becomes saturated ($E$, *fig. 8*) and, consequently, when passing the head, it is in the state $R_V$. A direct current is now superposed on the signal current of such strength that the point $A$ would be reached if no signal were present. In this case, on leaving the region of the head, the remanent magnetization is proportional to the signal field; if this is zero, the tape again becomes unmagnetized. Linearity can indeed be obtained by this method, and usable records can be made. However, the noise inherent in tape that has gone through this cycle is much stronger than that of a virgin tape. The causes of this phenomenon will be given later when discussing the problem of noise.

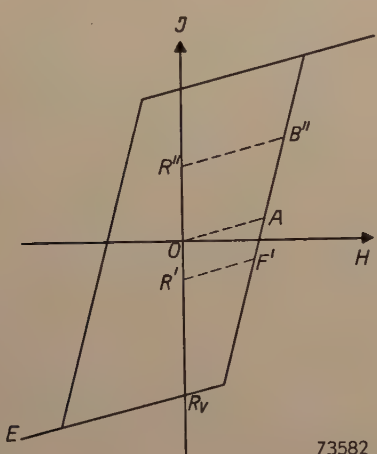



Fig. 8. D.C. biasing. The tape is first saturated ($E$) and then passed across the recording head. The direct current biasing field alone would lead to a state $A$; with modulation by the signal, such states as e.g. $B''$ and $F'$ would be reached. The remanence left in the tape after leaving the active field in the head is then O, $R''$ or $R'$.

Modern methods do not make use of a direct field; nowadays an alternating field is superimposed on the signal, of such a frequency that several cycles occur during the passage of the tape through the active portion of the stray field round the gap.

Assuming again a transport time for the tape of about $10^{-4}$ sec, it is clear that the frequency of this biasing field should be higher than $10^4$ c/s. In practice a much higher frequency is used, in the ultrasonic region, in the neighbourhood of $10^5$ c/s, so as to avoid the disturbing effects both of this frequency itself and of audible beat-tones between signal and biasing currents.

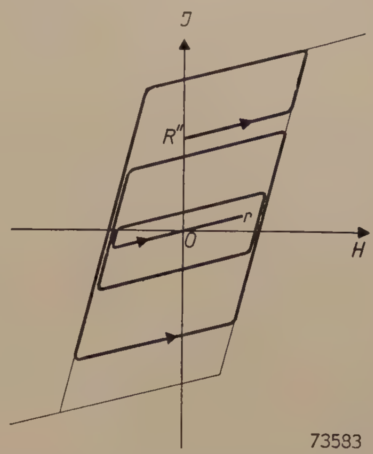



Fig. 9. The process of erasing. Imagine that the remanence $R''$ is the starting point. The increasing alternating field will saturate the material after a certain number of periods and make it traverse the large cycle. If now the intensity of the field decreases so slowly that the positive and negative peaks are nearly identical, the magnetization will follow the path shown till finally, the reversible branch $r$, through the origin, will be reached, reducing the remanence to zero.

The amplitude of this field will, of course, vary in the length direction of the tape. If this field alone is applied, a particle arriving at the gap will first be taken through several hysteresis cycles of increasing amplitude until it is saturated, and will then go through a number of diminishing cycles, so that it is demagnetized as it leaves the head. (*fig. 9*). This process occurs whether tape was previously magnetized or not, and is put to use in the erasing head.

Consider the case when the high-frequency alternating field is superposed on the relatively steady signal field of the head. Now the positive and negative peaks of the field are not situated symmetrically with respect to zero field, but are symmetrical about the field corresponding to the signal. If the amplitude of the alternating field is now decreased below the critical value $H_{cr}$, the magnetization process again becomes reversible, although these reversible states are not represented on a line through the origin but on a line parallel to that line (*fig. 10*). For simplicity, suppose that only the amplitude of the alternating field decreases as the tape moves, the signal field being substantially constant: then the remanent magnetization will be that corresponding to the signal field and this will remain even when, finally, the signal field, too, is removed. The final state is such that when all fields have been removed, a remanence $R''$ remains.

[5]) V. Poulsen (inventor of the magnetic recording method, see I) and P. O. Pederson, U.S. Pat. 873083, 1907.

The essential principle of the process is, therefore, the reduction of a hysteresis loop to a single reversible branch inside that loop. This transition takes place when the amplitude of the high frequency field (*i.e.* the difference in the value of $H$ at points $B'$ and $D'$, fig. 10) is exactly equal to 2 $H_{cr}$. The average value of the intensity of the signal field at that moment is the determining factor of the resulting remanent magnetization. This remains true though in reality its intensity changes at the same rate as the intensity of the alternating field, as the tape passes through the recording head. It is irrelevant that the signal field is not constant with time but is really a relatively slowly alternating field.

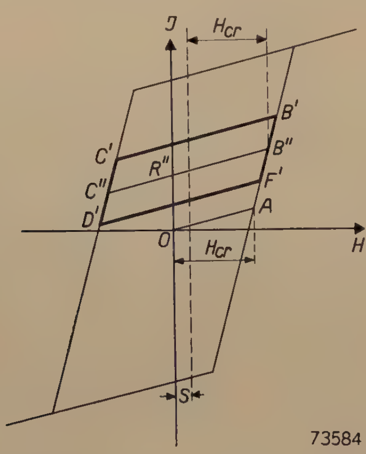



Fig. 10. Recording using a high-frequency biasing field. A rapidly alternating biasing field is superimposed on the constant field $S$. The positive peaks are always higher than the negative ones. When the biasing field has reached its maximum positive value in $B'$, the cycle $B'$ $C'$ $D'$ $F'$ is traversed. If the amplitude of the biasing field falls below the value $H_{cr}$, the magnetization remains on the reversible branch through $B''$; consequently, after taking away the biasing and signal field, the remanence $R''$ remains.

The remanence is always determined by the mean value of the two extreme field intensities (equal to the signal field) when the difference between them is exactly equal to twice the critical field intensity. This situation arises immediately after the gap has been passed, when the particle has already entered the decreasing part of the strong field: the above value of the remanence is now recorded on the tape.

## Distortion during recording

It is clear that owing to the introduction of the HF biasing field, the remanence has become proportional to the intensity of the signal field because the irreversible branch is represented by a straight line and all reversible branches are parallel to each other. Thus the distortion occurring in the absence of the biasing field has been eliminated in principle. A certain amount of distortion still remains, however, due to various causes.

Distortion is inevitable when the signal current is so strong that a higher field exists than that corresponding to the maximum remanence of the material ($R$, fig. 3). Consequently, care must be taken that the signal strength does not exceed a certain level.

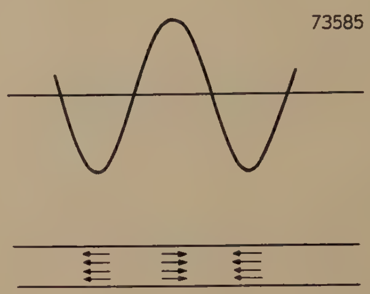



Fig. 11. Intense demagnetization occurs in the sound track of a sinusoidal signal with short wavelength (high frequency).

Distortion may also arise due to the demagnetization effect of adjacent parts of the tape. Consider, for example, a sinusoidal signal; if the positive peaks give rise to a magnetization directed to the right, the magnetization corresponding to negative peaks will be directed to the left (*fig. 11*). At the point under consideration, the oppositely directed magnetization in adjacent domains generate a field that tends to weaken the magnetization, especially when maxima and minima are close together (corresponding to shorter wavelength, i.e. higher frequency) and when the magnetization is strong. The relation between this demagnetizing field and the magnetization causing it, is represented in *fig. 12* for a fixed, low frequency, by the line $I$.

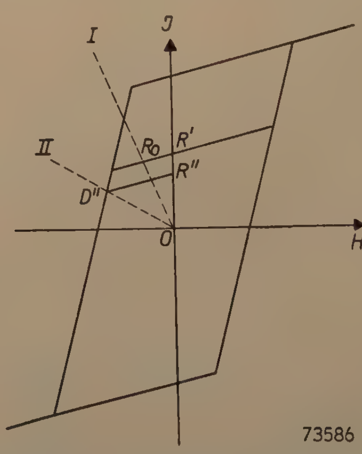



Fig. 12. As the demagnetizing field intensity is proportional to the magnetization, the resulting magnetization can be represented by a line through the origin, the slope of which is determined by the geometry of the magnetization pattern, for example, by the wavelength. With a small demagnetizing factor ($I$), the remanence $R_0$ is proportional to the signal, but not if the sloping line (e.g. $II$) and the reversible branch would intersect outside the hysteresis parallelogram.

When it has left the head, the part of the tape under consideration then attains a state corresponding to point $R_0$. As long as the reversible branches intersect the line $I$ at points within the hysteresis loop, the proportionality between signal and remanence is not impaired, not even when the demagnetization is diminished due to the magnetic "short-circuiting" effect of the soft iron of the reproducing head (as a consequence of this, the line $I$ in fig. 12 is replaced by a line with a steeper slope).

The proportionality is lost, however, when the intersection point would lie outside the hysteresis loop. In fig. 12 this is the case when, at higher frequencies, the demagnetization is represented by the line $II$. This causes a shift of the remanence from the line $R'R_0$ to the line $R''D''$.

## Optimum value of the biasing current

As is evident from the above, the linearity is influenced by the magnitude of the biasing current as well as by the strength of the signal. If the biasing current is zero, the magnetization is zero until the signal field $H$ exceeds $H_{cr}$; it then increases in proportion to $H—H_{cr}$, until saturation is reached. This is the large distortion mentioned in the beginning, which occurs when no biasing field is used.

Even when a biasing field is present, the same state of affairs is reached if its amplitude is too small, the only difference being that the increase in magnetization starts somewhat earlier. With a biasing-field amplitude equal to $H_{cr}$, the magnetization is proportional to the signal, except for the limits set by the saturation. In practice (for reasons to be given later) the biasing field in the neighbourhood of the gap is chosen higher than $H_{cr}$. In that case the signal is recorded on the tape a little further on, at the point where the biasing-field amplitude is exactly equal to $H_{cr}$. The more intense the biasing field, the further away from the gap this occurs and the weaker, at a given signal current, the operative signal field. The more intense the biasing field $H_b$, the more it must decrease to reach the value $H_{cr}$. The signal field must suffer a corresponding decrease; hence, for a given signal current, the remanent magnetization decreases as the biasing current increases.

These conditions are represented in *fig. 13a*. As the curvature of the line representing magnetization as a function of signal field is a measure of the distortion, it is clear that with weak signal currents, the distortion decreases with increasing biasing current ($H_b$). For strong signal fields, however, (depending on the exact values) the distortion first decreases with biasing field and may then suffer an increase due to saturation, followed by a further decrease. With average signal strengths the behaviour lies between those stated above.

In practice, a value of the biasing current is chosen such that it corresponds nearly to the secondary maximum for strong signals. This is a compromise, adopted because, as will be seen later, a higher value of the biasing current must be avoided, whereas with lower values, distortion may occur owing to the fall off in intensity of the field for particles furthermost from the tape surface.

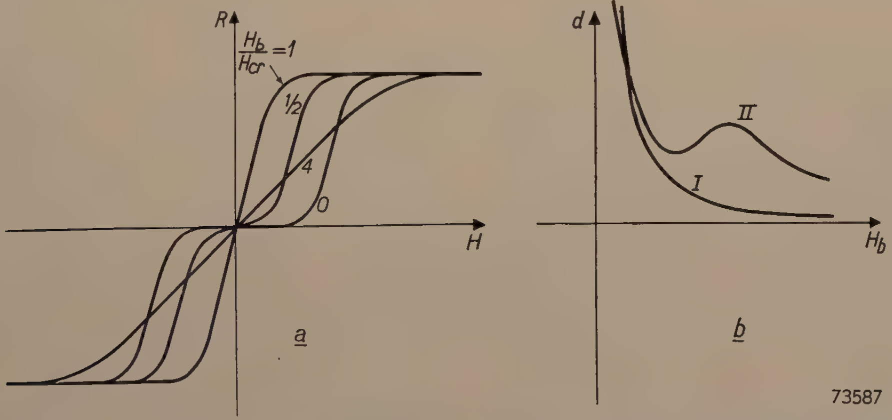



Fig. 13. *a*) Relation between magnetization and signal with various amplitudes of the HF biasing field $H_b$. *b*) Curve representing the distortion for a weak signal ($I$) and a strong signal ($II$), as a function of the HF biasing field.

## Effect of the biasing current on the frequency characteristic

The sound signal is recorded on the tape at the moment when the intensity of the biasing field is equal to $H_{cr}$; in practice, the value of $H_{cr}$ differs

slightly for different particles, so that there is a spread of the critical biasing field, and the signal is not completely recorded until the lowest value of the critical biasing field is reached. The position and the length of the recording zone of course depend on the strength of the current producing the biasing field. If during the recording of a rapidly alternating signal the value of the biasing field does not decrease quickly enough, it is possible that a part of the tape, after having passed the spot in which the intensity of the biasing field is exactly equal to the critical value, is brought again on the irreversible branch by the rapidly increasing signal field. This may cause a false rendering of the signal. The higher the signal frequency, the sooner this result is to be expected, because in that case the signal field, when passing the above-mentioned zone, changes in intensity more rapidly. This false rendering results in a certain attenuation of the recording of the high frequencies.

There are other and more important consequences of the differing coercivities among the particles of the tape. Two particles at the same spot on the tape but with different $H_{cr}$ values will not record the signal at the same moment and therefore will record a different phase. This phase shift of the signals on the sound track results in "interference attenuation" at high frequencies.

At a given biasing current, the points where $H = H_{cr}$ will not lie on a plane perpendicular to the tape, but on a curved surface. Consequently, particles with the same $H_{cr}$ but situated in different depths of the tape will meet the critical field intensity at different distances from the gap. This also makes the phase shifts of the recorded signal dependent on the depth in the tape. During *reproduction*, it is precisely those particles which lie instantaneously on the plane of symmetry of the gap which reproduce the signal, so that the summation of the out-of-phase signals again results in attenuation of the higher frequencies.

If the biasing current is stronger, the region where $H \approx H_{cr}$ lies farther away from the gap and is more extended. In this case the attenuation is noticeable at lower frequencies.

The distortion caused by demagnetization, mentioned earlier, which becomes worse with increasing frequency, can also attenuate the high frequencies, for, owing to this distortion, not only are the higher harmonics superposed on the fundamental, but the fundamental is itself attenuated.

It should be noted that the schematic representation of the magnetization process which has been used in this article, is only an approximation and cannot adequately explain every detail. To go into further detail would be to go beyond the scope of this article [6]).

**The reproduction process; influence on the frequency characteristic**

In order to convert the magnetic pattern on the tape back into an electrical signal, the tape is carried past the reproducing head, the construction of which is similar to that of the recording head (*fig. 14*).

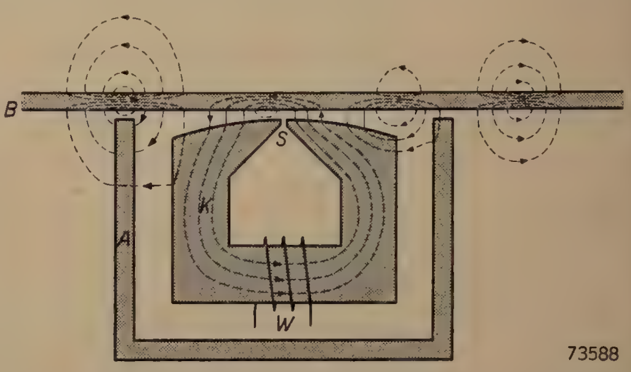



Fig. 14. Reproducing head $K$ with winding $W$, gap $S$ and screening $A$. $B$ represents the magnetized tape. The lines of force are indicated schematically.

Considering an arbitrary cross-section of the tape, the recorded magnetization $J$ gives rise to a total magnetic flux $\Phi$. As the lines of magnetic induction are always closed, they must close outside the tape, so that an equal and opposite flux is found there.

When the tape makes contact with the head, the lines of induction will close mainly via the material of the head (owing to its high permeability) and so link the reproduction coil. Thus a flux flows through this coil, which to a first approximation is equal to the flux traversing the cross-section of the tape facing the gap. When the tape moves on, changes of this flux induce the signal voltage in the coil. Due to the good magnetic conduction of the iron circuit, whereby the demagnetizing field is reduced, the flux mentioned is even greater than it would be with a tape moving freely in the air.

The closer the tape comes into contact with the head, the more will the demagnetizing field be reduced. If the surface of the tape is not completely smooth it will be in *true contact* with head only at certain points. In this case, the demagnetizing the field is not completely removed, and at small wavelengths a decrease in the magnetization will occur. This decrease will be greater as the slope of reversible branches becomes steeper (and thus the reversible permeability greater).

[6]) See W. K. Westmijze, Philips Res. Rep. 8, 148-157, 161-183, 1953.

It should be noted, however, that not all the induction lines will enter the pole pieces and hence do not all link with the coil. One reason for this is that the magnetic resistance of the iron circuit can never be quite zero, so that small magnetic potential difference will always remain across the gap $S$, and as a result, a flux proportional to this potential difference will pass across the gap. Therefore it is desirable to have a gap with a magnetic reluctance that is high compared with that of the iron circuit, i.e. a "long" gap with the small "height" [4]).

Taking into consideration constructional demands, namely the mechanical strength of the poles, the machining precision and the duration of life of the head, the height of the gap has been reduced as far as possible. It should be borne in mind that during use, the tape is moving continuously across the head at a high speed and with a fairly high pressure and that the magnetic particles of the tape are in fact a form of the well-known polishing agent jeweller's rouge. The resulting wear reduces the height of the gap to such an extent that after say, 500 hours, the head must be exchanged. The life time of the head of course also depends on other details of its construction and on the quality of the tape used.

A large gap length cannot be used, however, for more fundamental reasons: while it is true that for long wavelengths practically all lines of force emanating from the tape enter the poles and link with the coil, this is no longer true when the wavelength is comparable to the gap length. This occurs at relatively low frequencies if the gap length is

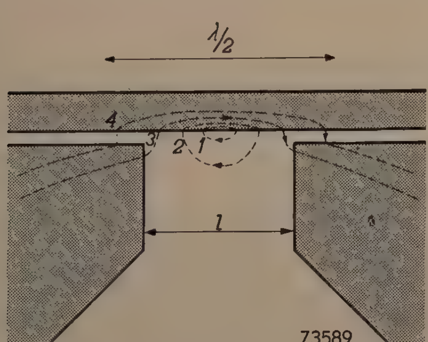



Fig. 15. The form of the induction lines, when the wavelength $\lambda$ is comparable with the length $l$ of the gap (the cause of the fall of the reproduction characteristics at high frequencies).

large. In this case a large number of the lines of force do not enter into the poles at all, but close through the air of the gap (*fig. 15*). To a first approximation this can be expressed as follows: the flux through the coil (gap length $= l$, wavelength $= \lambda$) is approximately proportional to

$$\frac{\sin(\pi l/\lambda)}{\pi l/\lambda}.$$

For small values of $l/\lambda$, i.e. if $\lambda \gg l$, this expression is practically equal to unity and independent of $\lambda$. With higher values of $l/\lambda$, i.e. at high frequencies, the value of the expression decreases and with it the frequency characteristic. If $\lambda = l$ and consequently $l/\lambda = 1$, the expression $= 0$ and no flux at all flows through the coil. Therefore the gap must be shorter than the smallest wavelength essential for reproduction.

A second cause for the lines of force not linking with the head lies in the fact that at very long wavelengths (*fig. 16*) the lines of force take a path

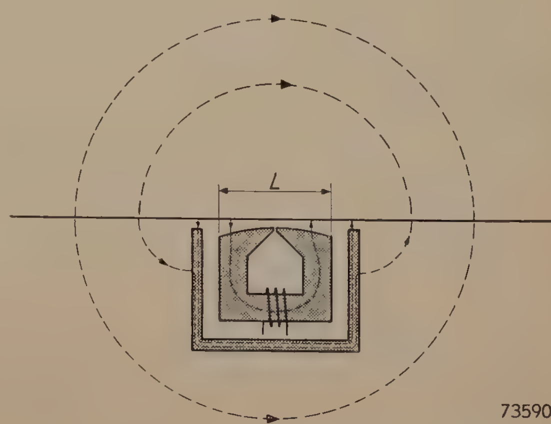



Fig. 16. The form of the lines of induction, when the wavelength is comparable to the dimension $L$ of the head (a source of irregularities in the frequency characteristic at low frequencies).

around the head, especially so when it is surrounded by the inevitable shielding ($A$). Supposing now that only the lines of force over a certain length $L \gg l$ of the tape contribute to the flux through the coil, the flux becomes proportional to:

$$\int_0^L \sin(2\pi x/\lambda)\mathrm{d}x = \frac{\lambda}{2\pi}\left[1 - \cos(2\pi L/\lambda)\right].$$

This means that for wavelengths $\lambda \gg L$ only a negligible part of the flux traversing the tape at the point where it faces the gap, enters the coil. As the wavelength decreases, a maximum is reached for $\lambda = 2L$, and with still shorter waves, maxima and minima ($=$ zero) would alternate for $L = (n+{}^1/_2)\lambda$, and $L = n\lambda$, respectively, in which $n$ represents a whole number. This is not so serious as it sounds, because the transition between the flux making its way through the coil and the flux taking other paths is not sharp but gradual, which

results in the maxima and minima being smoothed to a considerable degree, making them imperceptible for $\lambda \ll L$. Consequently, the result of this effect is mainly a decrease in the useful flux for wavelengths greater than $L$ (*fig. 17*).

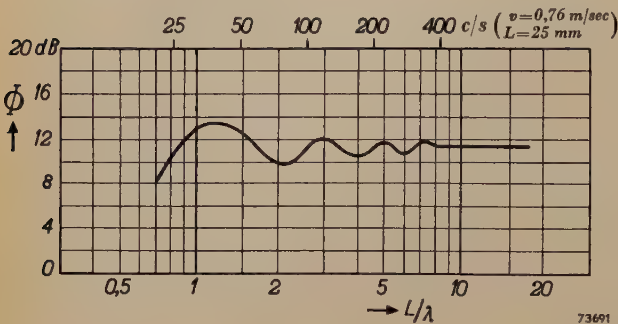



Fig. 17. The form of the useful flux $\Phi$ (in dB) as a function of the wavelength at long wavelengths. $\Phi$ is plotted against $L/\lambda$ (thus the frequency increases from left to right). If $L =$ 25 cm and the speed of the tape = 0.76 m/sec, the maximum at the left corresponds to a frequency of 37 c/s.

In general, the decrease of the useful flux at *short* wavelengths is more serious than at long wavelengths. The frequency at which this decrease occurs can in principle always be raised by increasing the speed of the tape. In practice the tape speed is increased to such a value that the remaining frequency correction can be successfully applied in the amplifier, without introducing too much noise and other disturbances. On the other hand, the amount of tape used becomes larger and the playing time decreases when the speed of the tape is increased. Moreover, the decrease of the useful flux at longer wavelengths, which corresponds at small speeds of the tape with frequencies below the audible range, is noticed as an irregularity in the characteristic and as an attenuation at lower, audible frequencies. It will also be seen below, that at higher tape speeds the "print-effect" becomes stronger at higher frequencies (and consequently becomes more disturbing). On account of this it is necessary to choose a tape speed which is a compromise between the reproduction of the high frequencies and the objections just mentioned.

### Overall frequency-characteristic: "transimpedance"

In the preceding section the influence of the recording and the reproducing process on the frequency characteristic have been discussed separately. In practice it is difficult to separate the one influence from the other, as the magnetization brought about by the recording process can be measured only with a reproducing head. The voltage generated at the reproducing head can then be measured as a function of the current sent through the coil of the recording head. If we assume that this current is a pure sinusoidal current the relation between the voltage and the current mentioned can be determined as a function of the frequency $f = \omega/2\pi$. This relation has the dimensions of an impedance and may therefore be called the "transimpedance".

If it is desirable to study the influence of one of the components of the system — recording head, tape or reproducing head — separately, this can only be carried out by relative measurements, which means that one of the components should be replaced by a corresponding part and a comparison made between the transimpedance measured before and after the exchange.

Ideally, i.e. excluding very low and very high frequencies, the transimpedance increases linearly with the frequency. It is therefore comparable with the impedance of an inductance.

The transimpedance depends not only on the frequency but also on the number of turns of the coils of both heads. Within certain limits we have a free choice in these, and thus the value of the transimpedance can still be varied at will.

Sometimes it is useful to consider, apart from the transimpedance $Z_{12}$, another quantity which it is convenient to call the "transfactor" ($T$), defined by the relation:

$$T = \frac{Z_{12}}{(Z_1 Z_2)^{1/2}} .$$

($Z_1$ is the impedance of the recording head, $Z_2$ that of the reproducing head.)

This factor is dimensionless, and is independent of the number of turns of the coils. In the ideal case it is a constant, independent of the frequency (*fig. 18*), of magnitude about 0.01.

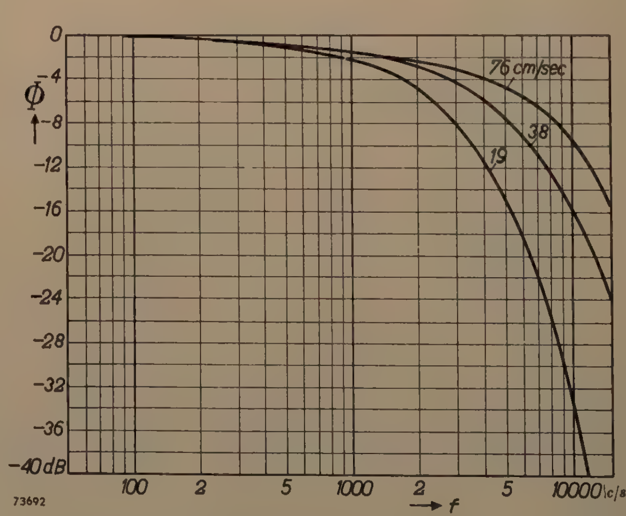



Fig. 18. Corrected frequency-characteristic (flux $\Phi$ through the reproducing head) for tape velocities of 19, 38 and 76 cm/sec resp. At the same time the curves approximately represent relative values of the transfactor as a function of the frequency $f$.

## Noise

### *Ground noise*

The magnetic layer of a recording tape is built up from very small particles. If the layer is examined under an electron microscope, the size of the particles (*fig. 19*) is found to be about 0.1 μ. Now we can assume that every particle still contains some Weiss domains, separated by walls. If the tape is completely demagnetized, the fields of the Weiss domains will largely compensate each other, but still a weak, multi-polar field will emanate from every small particle. As a result of this, some lines of force will leave the material and create a micro-field, which irregularly changes its sign along the tape. This micro-field is easily detected by running the tape across the reproducing head, with its narrow gap of 10 μ. If then, a demagnetized or virgin tape is carried across the reproducing gap, it will continuously induce low irregular voltages into the coil of the head, which, after amplification, are audible as noise, the ground noise. This noise limits the weakest signal still reproducible and determines in that way the "dynamic range". By this we understand the difference in level, measured in dB, between the largest signal which can be recorded without appreciable distortion and the smallest signal still audible above the ground noise.

In general, the more particles available to record the signal, the larger the dynamic range. If the average size of the particles is 0.1 μ, and the tape velocity is 0.76 m/sec, with a tape of width 6.3 mm and a magnetic layer thickness of 15 μ, the number of particles passing the gap per second will amount to about $10^{13}$. A simple calculation of probabilities shows that in the frequency range $0<f<10^4$ c/s the dynamic range will be at least 90 dB (in reality, due to partly unknown causes, about 70 dB is usually measured).

### *Modulation noise*

A magnetized tape possesses more noise than a clean tape. It is true that this higher noise level is partly masked by the signal, but it is still audible, especially when the signal consists of a single note (pure sine function), which now sounds somewhat harsh. In order to understand this extra noise, it is necessary to consider the structure of the tape. The particles of the magnetic material are not evenly distributed through the carrier, but are grouped in clusters (fig. 19). In the demagnetized state, in every cluster the magnetic moments of the separate particles are irregularly distributed. In the magnetized state, in every cluster a more or less evenly directed magnetization of the particles is present. Due to the distance between the clusters and due to the fact that each cluster now represents a dipole, there is more chance that lines of force from the microfield will emerge outwards. This may also be expressed in the following way. Due to the grouping of the particles in clusters, the sensitivity of the tape shows fluctuations over long distances as well as short ones [7]). This causes the signal to be multiplied by a factor which is a function of the point $x$ on the tape. If we call this factor $1+\delta(x)$, it is found that $\delta(x)$ irregularly changes its polarity, even in an interval comparable with the smallest wavelength which can be registered. Still another way of expressing this would be to say that an interference signal $S(x)\cdot\delta(x)$, proportional to the signal, is superimposed on the signal $S(x)$. The noise caused by this is called the modulation noise. The ratio of signal/modulation noise is about 40 dB.

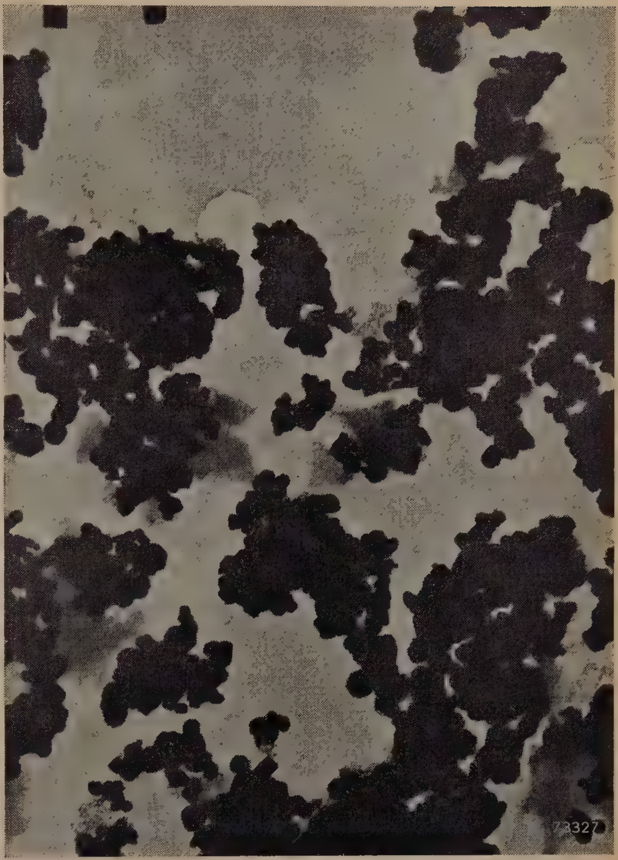



Fig. 19. Electron microscope picture of a thin layer of the coatings covering the magnetic tape. Enlargement 10,000 ×. The separate particles (size ≈ 0.1 μ) group together in clusters.

The measuring of the modulation noise is carried out by passing a direct current (in addition to the biasing current) through the recording head, equal

[7]) Fluctuations in the thickness of the magnetic layer, which may occur up to 1%, have the same effect.

in amplitude to the maximum admissible sinusoidal signal, and to measure the voltage induced in the reproducing head. Clearly a D.C. magnetization of the tape should always be carefully avoided, as the modulation noise of this D.C. magnetization would always be present. This magnetization may be caused, for example, by a permanently magnetized recording head, or a D.C. component of the biasing current. Even if the biasing current does not contain a D.C. component, it can cause D.C. magnetization, viz. when the positive and negative peaks differ in height. This is a result of the specific property of the tape to react only to the peaks of the magnetic field. It can now also be understood why the Poulsen method of using a D.C. biasing field may cause a higher noise level in the tape, especially in the weaker passages. This noise would not arise if the opposing field could exactly eliminate the D.C. magnetization; incomplete compensation, however, leaves a remanent magnetization in the tape. The advantage of the application of an HF biasing field is that, when no signal is present, the tape is automatically left in the demagnetized state.

**Print-effect**

If the magnetic material really behaved as suggested by the scheme given in fig. 3, only exterior fields of higher intensity than the critical value would be able to affect the recording. Such a strong field will not readily occur accidentally under ordinary circumstances. If appears, however, that weak fields, e.g. those originating from an adjoining layer in a rolled tape, may also influence the magnetization. Consequently, if parts of a tape carrying a very weak part of the recording happen to lie near parts where a sudden strong signal occurs, a part of the magnetization due to the latter signal may be transferred to the adjacent layer. In this way the strong signal may be weakly audible during reproduction once or even a number of times, before and after the real signal. This is the so-called "print-effect". The transfer of magnetic energy is here effected by the thermal agitation. For the reversal of the magnetization of a Weiss-area, a certain amount of energy $E$ is required. Till now we have considered only the case when this energy is completely supplied by an exterior magnetic field. It can, however, also be supplied partly by the thermal agitation. The probability of a transition from one orientation to another as a result of the thermal agitation is given by the well-known expression exp $(-\Delta E/kT)$, where $\Delta E$ represents the energy required for the transition, $k$ the Boltzman constant and $T$ the absolute temperature. When an equilibrium has set in, a weak field, in itself not strong enough to supply the energy for reversing the magnetization (i.e. roughly speaking, smaller than the local coercive force) may still cause a shifting of the equilibrium with the aid of the thermal agitation. After the interfering field has been removed the area does not resume its original state, at all events, not at once. It appears that the print-effect, as would be expected on this theory, strongly increases with increase of temperature, and is also dependent on the duration of the influence (it increases almost linearly with the logarithm of time, (*fig. 20*). When the field is removed it decreases

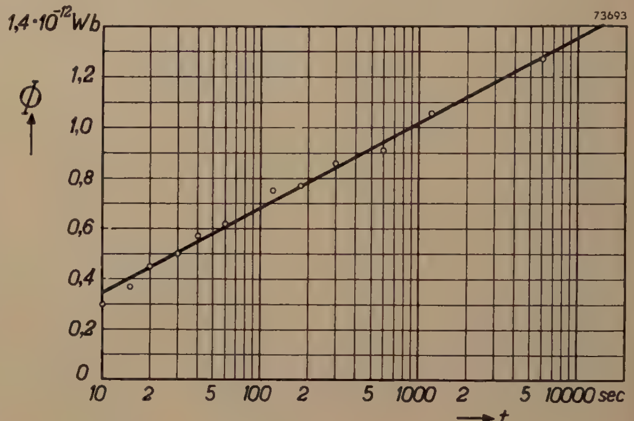



Fig. 20. Measured "print-effect" plotted as a function of the duration of the influence (log. time-scale). The graph shows the flux $\Phi$, caused in a clean tape by contact with a tape at 30 °C having a saturated varying signal of wavelength 0.5 mm.

again, but it does not disappear completely, as there will be some particles in such a stable state that it is highly improbable that they will return to their original state by the thermal agitation.

It will be understood that stray AC fields can also take over the part played by the thermal agitation and may cause an increase of the print-effect. With the aid of a high-frequency A.C. field it is even possible to transfer the recording from one tape to another in contact with it. In this way contact copies can be made [8]) in a manner similar to photographic processes.

The print-effect is not equally strong for all wavelengths. The magnetizing field is in reality the field of the neighbouring layer, the distance between this and the magnetized layer being equal to the thickness of the tape. The intensity of this field decreases exponentially with the ratio of the tape thickness ($\Delta$) to the wavelength ($\lambda$), but it is also proportional to the ratio $d/\lambda$, in which $d$ represents the thickness of the magnetic layer, which is nor-

[8]) M. Camras, Electronics 22, Dec. 1949, p. 78.

mally smaller than $\Delta$ (*fig. 21*). This is expressed in the formula

$$\mu_0 H = \frac{\pi d}{\lambda} \cdot B_0 \cdot \exp(-2\pi\Delta/\lambda),$$

where $B_0$ represents the average induction in the magnetized layer. The formula shows that the strength of the field has a maximum value when

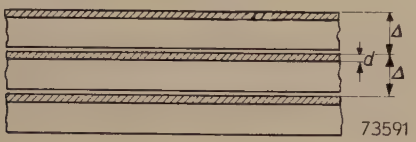



Fig. 21. Some layers of rolled tape. The figure shows the relative dimensions of the tape-thickness ($\Delta$) and the thickness of the magnetic layer ($d$).

$\lambda = 2\pi\Delta$. When the thickness of the tape $\Delta = 55\ \mu$, this maximum is reached for $\lambda = 350\ \mu$, which with a tape speed of 0.76 m/sec. corresponds to a frequency $f = 2200$ c/s. This frequency is lower at smaller tape speeds, so that the audibility of the print-effect is then less.

## Comparison of the magnetic process with other recording methods

In comparison with other sound recording and reproducing methods, the magnetic process has both its advantages and its disadvantages.

At the speeds used for professional purposes, i.e. at a tape speed of 30″/sec = 0.76 m/sec, the quality of the sound reproduced is superior to that of all other systems, thanks particularly to the favourable signal/noise ratio, which is perhaps equalled by that of a newly cut lacquer disc. The dynamic range of the gramophone records commercially available and of the optical systems (photographic and Philips-Miller processes) is certainly smaller.

Since, in optical processes, the number of electrons emitted by a photo-electric cathode is of the same order of magnitude as the number of magnetic particles passing the reproduction head per second in the magnetic process, it might be expected that the two systems would exhibit roughly the same dynamic range. However, the number of electrons emitted is not the only factor which influences the dynamic range in optical processes. The noise in optical systems is also dependent on a variety of other causes, e.g. the grain of the film and small irregularities in the film.

Another advantage of the magnetic process lies in the fact that both the negative and the positive magnetization contribute to the recording, which makes the "zero track", necessary in optical recording, superfluous. This eliminates the noise generated by a zero track, and at the same time, the necessity to suppress the zero track during weak passages ("noiseless reproduction").

Magnetic recordings are free from noise caused by dust particles, an additional source of noise found in all other systems. Dust particles are normally non-magnetic, so they do not contribute to noise in the magnetic process.

On the other hand, disturbing magnetic fields may unfavourably influence the magnetic recording, especially as regards the print-effect, which is not present in other recording processes. For some purposes the fact that the modulation is not visible may be a disadvantage. Nevertheless, the magnetic process is being used more and more in studios for broadcasting, and as an intermediate link in the gramophone and film industries.

The simple handling, during both recording and reproduction, is an important feature. This is especially important for the recording process, where, in all other systems, an expert technician is needed. The door is thus opened to a large number of amateur or semi-professional applications, at home, in the office, and for studying music or languages. The simplicity of the apparatus makes a compact construction possible, a very important feature for designing portable equipments.

A unique advantage of the magnetic process lies in the fact that a recording can be erased and a fresh one recorded at once. This has considerable economic advantages in some applications, and also

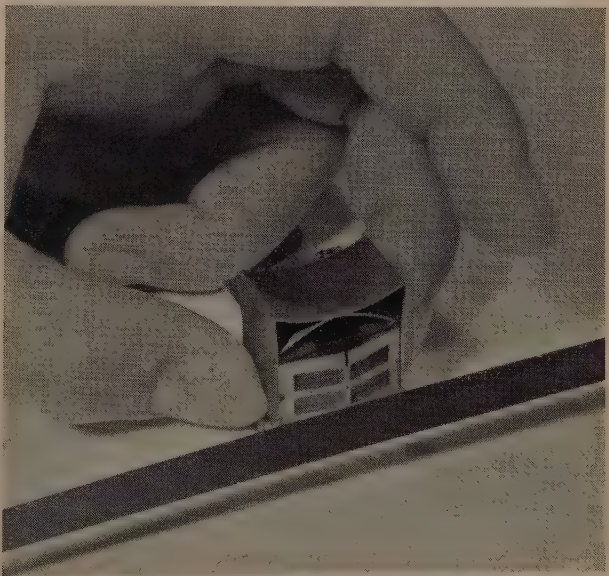


Fig. 22. Recording head for the stereophonic recording of sound on a magnetic tape.

opens the door to a number of quite new possibilities, e.g. the magnetic recording of data in the "slow-memory" of modern computing machines. In this way intermediate results may be stored until needed for further computations.

As a tape is used in the magnetic process, it is very suitable for stereophonic recordings. This is also the case with the optical and with the Philips-Miller systems, but it is more difficult to achieve with the gramophone record. The two sound tracks necessary for stereophonic reproduction can be recorded side by side by using a double recording head (*fig. 22*) and similarly reproduced later on.

**Summary.** The processes occurring during the magnetic recording and reproduction of sound on a ferromagnetic tape are discussed in detail with the help of a simplified representation of the hysteresis loop and of the magnetization process in the iron-oxide particles of the tape. Linearity between signal and magnetization is attained by the application of a high-frequency biasing field. The strength of the biasing field influences both the linearity of the signal and the frequency characteristic. Distortion and attenuation of the high frequencies during recording may also be caused by demagnetization processes. Deviation from the flat characteristic during reproduction occurs with long waves (low frequencies) as well as with short waves (high frequencies). In the latter case, the tape speed together with the length of the gap of the reproducing head determine the highest frequency which can be reproduced. When further discussing the total frequency characteristic, it is useful to introduce the concepts "transimpedance" and "transfactor". The noise of the tape is determined largely by the grain structure. An additional noise (modulation noise) sets in during magnetization, as a result of fluctuations in the thickness of the magnetic layer and the grouping of the magnetic particles into clusters. The transfer of magnetization to another tape is sometimes useful (for copying purposes), and at other times deleterious (print effect).

A comparison of the magnetic recording process with other recording processes shows that the quality of sound reproduction of the magnetic process is superior, in many respects, to others. Moreover, the specific qualities of this system (easy handling, erasure) favour its use in many applications.

# METAL-DETECTORS

by E. BLASBERG and A. de GROOT.

621.318.4: 621.317.18: 669-493

*In many manufacturing processes, the detection of metallic inclusions is of great importance. Examples are in the textile, paper and plastics industries, where small metal particles may damage the machinery or spoil the finished product. Undetected pieces of metal such as nails or parts of tools in timber or coal may have serious consequences in sawing or crushing operations. Many devices have been designed for the detection of metal objects in non-metallic materials. In the present equipment, intended specially for tracing extremely small particles of metal, the sensitivity has been increased to a point where it is possible to detect iron particles as small as 0.1 mg and non-ferrous particles down to about 0.4 mg.*

During the manufacture or processing of non-metallic materials the intrusion of metal particles into the raw material or finished article is very difficult to avoid. In many cases this may be disastrous to the quality and good name of the article, apart from the damage that such metal particles can cause to the processing machines. It is often difficult or even impossible to see the foreign body and remove it in time, for example when it is buried beneath the surface of the material; the inspection, moreover, demands constant attention on the part of the personnel.

Efforts to eliminate the human element and to provide a more reliable check than is possible by mere *visual* inspection, have led to the development of special equipment — metal detectors — sensitive to metal particles, which gives a warning signal when such particles are encountered [1]). If desired, the particular machines can be stopped automatically, or that part of the material which contains the metal can be removed.

Many metal-detectors are intended only to indicate the presence of fairly large metal objects, such as nails or bullets in trees which are to be cut into planks, or small tools amongst coal being fed to a crushing machine. In other instances it may be desirable to detect extremely small particles of metal — for example, during the manufacture of gramophone records — even a very small metal particle in the plastic moulding materials can put a whole matrix out of action. In textile factories, too, a small metal object such as a pin or wire staple will often cause much damage to both machine and product.

A description is given in this article of two units which were specially designed for the inspection of non-metallic materials for the presence of small metal particles. The first of these is intended for the inspection of bulky materials in bales or on conveyor belts, packed foods and so on, whereas the second is more for the detection of iron particles in materials in the form of a long strip, such as paper or fabrics.

## Metal-detector for bulk materials

### *Description of the detector*

The principle on which this detector works may be seen in *fig. 1*. The material to be inspected moves on a conveyor belt $A$ through a set of four coils $L_1$, $L_2$, $L_3$ and $L_4$. Of these, the so-called generator coils $L_1$ and $L_2$ are wound in the same direction and

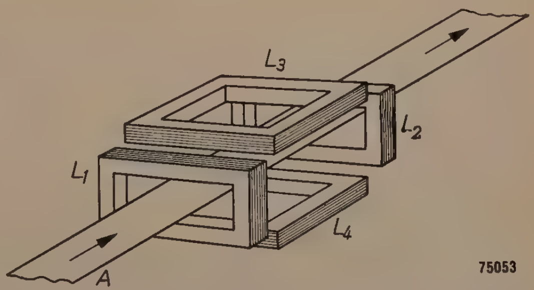



Fig. 1. Diagram showing arrangement of the coils in a metal-detector for bulk materials. The material to be inspected lies on the conveyor belt $A$. $L_1$ and $L_2$ generator coils. $L_3$ and $L_4$ pickup coils.

are connected in series; they carry an alternating current of 1400 c/s. *Fig. 2*, which depicts a cross-section of this coil system, also shows diagrammatically some of the lines of force of the magnetic field that occurs in and around the coils. As will

[1]) See G. S. Elphick, A. R. Woods and S. Y. Logan, Metal detection in industry, Symposium on electronics, Chapman and Hall, 124-139, 1949.
C. R. Schafer, Industrial Metal Detector Design, Electronics, **24**, 86-91, Nov. 1951.
M. Grobtuch and D. J. Williams, Pulp-Log Metal Detector, Electronics, **25**, 124-126, July 1952.
W. Zandra, Ein neues Metallmeldegerät, Elektrotechn. Z. **73**, 487-489, 1952.

be seen, coils $L_3$ and $L_4$, the "pickup" coils, include lines of force emanating from both $L_1$ and $L_2$, these lines cutting the coils in opposite directions. When the whole system is in equilibrium, no voltages are

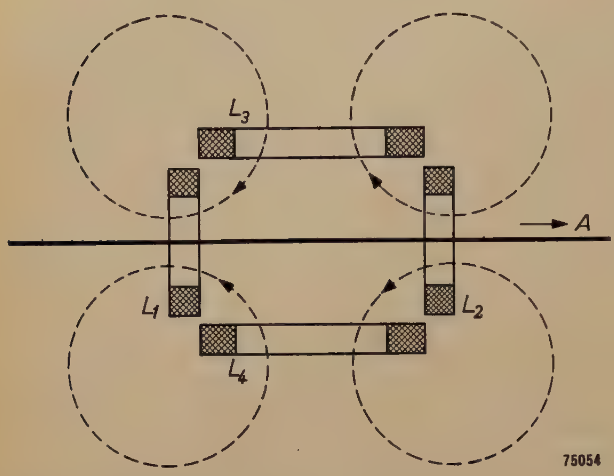



Fig. 2. Cross-section of coil system shown in fig. 1. The broken lines indicate the mean magnetic lines of force.

induced in $L_3$ or $L_4$, but, should there be a metal particle in the material under inspection passing through on the belt $A$, this will, if it enters coil $L_1$, modify the lines of force of this coil. The balance between the voltages induced in $L_3$ and $L_4$ by $L_1$ and $L_2$ is thus disturbed, and an A.C. voltage occurs in $L_3$ and $L_4$. Now, as these coils are wound in opposite directions and are connected in series, they will supply an A.C. voltage to the amplifier to which they are connected. The amplified voltage can be applied to a relay to operate a warning system or to switch off a motor.

An $RC$ oscillator is employed as generator, this being a simpler way of producing a stable frequency and constant output voltage than by means of an oscillator with $LC$ circuit. The oscillator is coupled to a push-pull amplifier with phase-inverter valve in accordance with the circuit dagram shown in *fig. 3*. The oscillator proper comprises valves $T_1$ and $T_2$, a network $R_1$-$C_1$-$R_2$-$C_2$ producing positive feed-back; negative feed-back is provided through $R_3$ and $R_4$. For this circuit to oscillate, the alternating anode voltage from $T_2$ must be in phase with the alternating grid voltage of $T_1$ and, as will be seen from a simple calculation, this takes place with an angular frequency given by:

$$\omega^2 = \frac{1}{R_1R_2C_1C_2}. \quad . \quad . \quad . \quad . \quad . \quad (1)$$

When $R_1$ is of the same value as $R_2$, and $C_1$ the same as $C_2$, as is usually the case in $RC$ oscillators:

$$\omega = \frac{1}{R_1C_1} = \frac{1}{R_2C_2}. \quad . \quad . \quad . \quad . \quad (2)$$

The ratio of the A.C. anode voltage from $T_2$ to the A.C. grid voltage of $T_1$ is then 3 : 1, from which it follows that the amplification of the two valves need be only 3 for oscillation to occur. Without the negative feed-back already mentioned ($R_3$,$R_4$), the gain would be much greater, but it automatically adjusts itself to 3 in view of the fact that $R_3$ has a high negative temperature coefficient (NTC resistor [2]). When a current flows in this kind of resistor, the temperature rises and the resistance

[2]) See E. J. W. Verwey. P. W. Haayman and F. C. Romeyn, Semi-conductors with large negative temperature coefficient of resistance, Philips tech. Rev. 9, 239-248, 1947/1948.

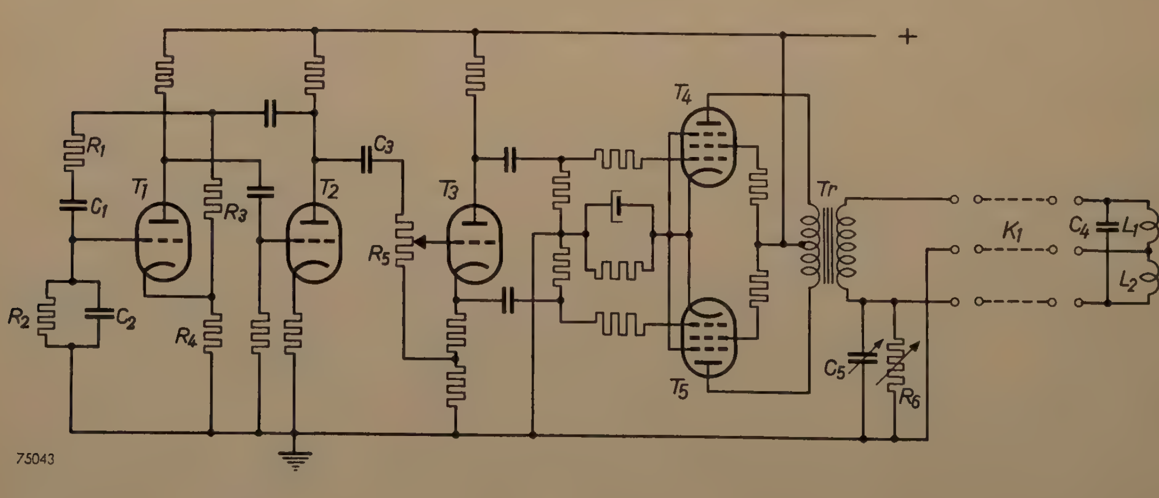



Fig. 3. Circuit diagram of the generator section of the metal-detector. Valves $T_1$ and $T_2$ constitute an $RC$ oscillator. $T_3$ is an amplifier and phase-inverter valve; $T_4$ and $T_5$ are output valves. $K_1$ cable connecting the unit to the generator coils $L_1$ and $L_2$.

drops. The negative feed-back factor in the circuit therefore increases when the voltage across $R_3$ rises, and this will occur as long as the gain from $T_1$ and $T_2$ (allowing for the negative feedback) exceeds a factor of 3.

If the amplification is very high, so that a considerable negative feed-back is necessary, a voltage division will take place across $R_3$ and $R_4$ in a ratio that is practically the same as that of the voltage dividing network $R_1$-$C_1$-$R_2$-$C_2$ which, as already mentioned, is 3 : 1. The output voltage of the $RC$ oscillator accordingly rises [3]) to a level where $R_3$ is almost equal to 2 $R_4$. For further details of this type of oscillator reference may be made to other publications [4]).

The voltage delivered by the oscillator is applied through a capacitor $C_3$ and volume control $R_5$, to the grid of $T_3$, from the anode and cathode of which two voltages are obtained, of opposite phase, which are in turn fed to the two push-pull valves $T_4$ and $T_5$. A cable $K_1$ is used to connect the output transformer of the oscillator to the two generator coils $L_1$ and $L_2$. Together with capacitor $C_4$, these coils form an oscillatory circuit tuned to a frequency of 1400 c/s. As it is a practical impossibility to make these coils absolutely identical, a variable resistor $R_6$ and variable capacitor $C_5$ are connected across one of them, enabling the current flowing in it to be adjusted so that the sum of the induced voltages in $L_3$ and $L_4$ (see figs. 1 and 2) will be exactly zero.

*Fig. 4* shows the skeleton circuit diagram of the amplifier and detector section, to which the voltage induced in the pickup coils $L_3$ and $L_4$ is applied via a cable $K_2$. This section comprises a two-stage amplifier $V_1$ for amplification of the A.C. voltage induced in $L_3$ and $L_4$. Although only a voltage of fixed frequency is applied to the amplifier, it is essential that the amplifier should have a certain minimum selectivity, as the gain is fairly high, and this helps to reduce the noise originating in the initial stage of the amplifier. Again, it is undesirable to amplify harmonics of the oscillator frequency, for the following reasons. The A.C. voltage applied to the coils $L_1$ and $L_2$ by the oscillator is not purely sinusoidal. The "equilibrium", in which the sum of the induced voltages in $L_3$ and $L_4$ is zero, cannot be obtained simultaneously for voltages at the fundamental frequency and its harmonics. By designing the amplifier to be fairly selective, these two difficulties of the equilibrium adjustment are avoided. Two filters are used to give the required bandwidth.

The A.C.voltage delivered by the amplifier $V_1$ is rectified by a diode $D$ and, when a metal object passes through coils $L_1$ and $L_2$, the voltage induced in $L_3$ and $L_4$ is modified, and the D.C. voltage supplied by the diode varies. The resultant voltage impulse is amplified by a two-stage amplifier $V_2$, the output voltage of which is applied to the grid of a thyratron $Th$; the phasing is such that when the A.C. voltage applied to the diode $D$ rises, a positive voltage impulse occurs on the grid of $Th$, which then strikes.

The voltage from the diode $D$ is simultaneously passed to the grid of an electronic tuning indicator $TI$, to facilitate adjustment of the equipment. This is done by adjusting resistor $R_6$ and capacitor $C_5$ in the oscillator section (fig. 3), so that the total voltage induced in the pickup coils is as small as possible; the fluorescent part of the tuning indicator is then at its minimum.

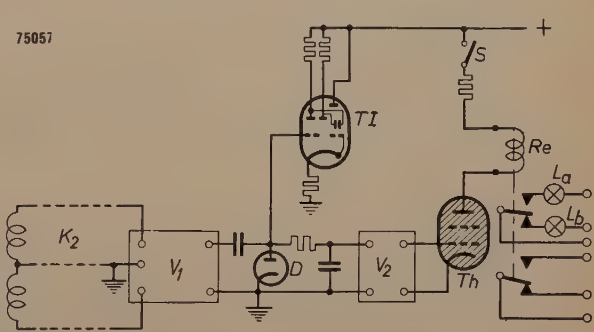



Fig. 4. Circuit diagram of the amplifier and detector section of the metal-detector. $V_1$ 4-stage amplifier for the voltages at the generator frequency of 1400 c/s. The voltage rectified by the diode $D$, is amplified in a 2-stage amplifier $V_2$, being simultaneously applied to an electronic tuning indicator $TI$. A relay $Re$ is included in the anode circuit of the thyratron $Th$. $S$ switch for quenching the thyratron; $L_a$ and $L_b$ signal lamps.

The amplifier $V_2$ is not a D.C. amplifier: capacitors are used for coupling purposes. A slow drift in the equilibrium adjustment (minimum induced voltage in the pickup coils) is unavoidable; the causes of this may be temperature variations, or vibrations to which the apparatus may be subjected. If $V_2$ were a D.C. amplifier, it would respond to these slow changes, even in the absence of metal near the coils. However, as $V_2$ is an A.C. amplifier, only rapid changes in the voltages induced in $L_3$ and $L_4$ operate the warning system.

[3]) The NTC resistor is the limiting element in this circuit. If this method of limitation is not employed, the output voltage is usually limited by the occurrence of grid current or curvature in the valve characteristic. In this case distortion of the output voltage is much more pronounced.

[4]) M. G. Scroggie, Audio signal generator, Wireless World **40**, 294-297 and 331-334, 1949.
J. McG. Sowerby, Selective *RC* circuits, Wireless World **41**, 223-225, 1950.
D. J. H. Admiraal, *RC* oscillators, Electronic Applications Bulletin **12**, 111-131, 1951.

In order to prevent the condition of equilibrium from being disturbed too much by effects such as those described above, the unit should be set at regular intervals to give minimum deflection of the tuning indicator.

*The sensitivity*

The sensitivity of the equipment drops as the generator and pickup coils are made larger. It has been found in practice that with coils 16 sq. cm in area an iron particle 0.1 mg in weight can be detected. To illustrate the relationship between the voltage delivered by the amplifier and the particle size of the iron, *fig. 5* shows the A.C. output voltage plotted as a function of the thickness of a cylindrical iron particle placed coaxially in the coil, for different particle lengths. The coil area in this case was 100 cm². From this figure it will be seen that, provided the particle is not too small, the voltage obtained is a linear function of the particle thickness.

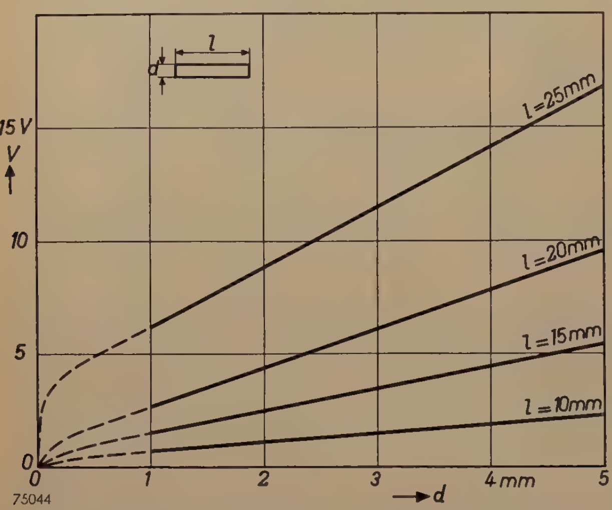



Fig. 5. Voltage V delivered by the amplifier $V_1$ (see fig. 4) as a function of the diameter *d* of a cylindrical iron particle of length *l* placed in one of the generator coils. Aperture of the coils: 10 cm × 10 cm.

As the voltage induced in the pickup coils, for a given flux, is proportional to the frequency, the sensitivity will in the first instance increase with frequency, but here it is necessary to make a distinction between iron and non-ferromagnetic metals. As the frequency is increased, more and more eddy currents are produced in the foreign particles; the detection of non-ferromagnetic objects is based on this fact, so that a high frequency is advantageous for two reasons. On the other hand, with iron particles, which are detected by reason of their high permeability, such eddy currents are undesirable as they reduce the effective permeability, so that on this score, the frequency should not be too high. In a number of units a frequency of 1400 c/s has been employed, this being the frequency at which the results shown above were obtained. For most of the metals in general use, the specific resistivity of which is not so low that the occurrence of eddy currents is greatly hampered, e.g. copper, brass,


Fig. 6. View of the oscillator section of the metal-detector for bulk materials.

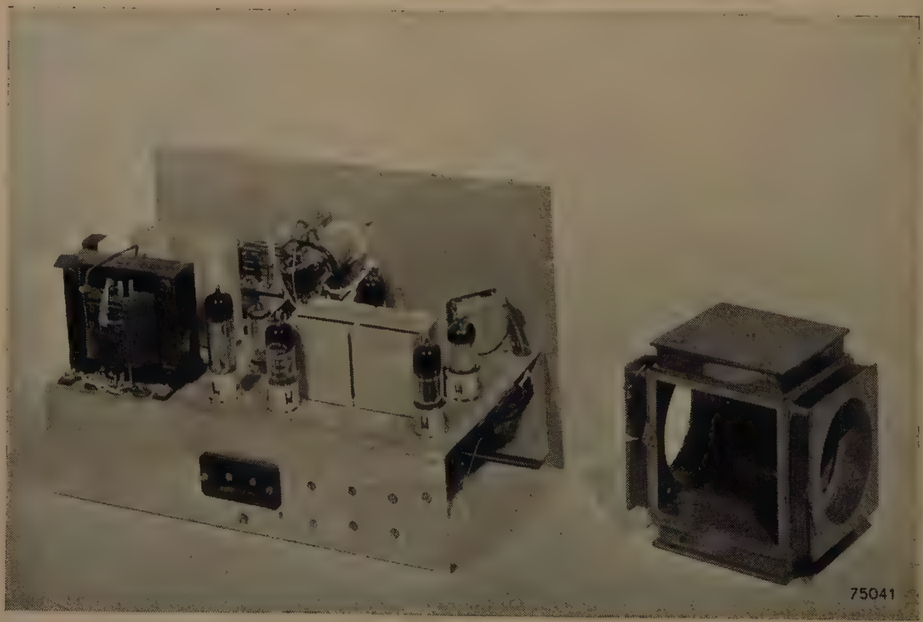



Fig. 7. The amplifier and detector section of the metal-detector for bulk materials. At right: coil system.

aluminium, the voltage induced in the pickup coils at a frequency of 1400 c/s is roughly one quarter of that produced by the presence of iron particles of the same size.

If the equipment is to be highly sensitive, every care must be taken to ensure a constant anode voltage for the valves, since small variations in this voltage will have the same effect as the appearance of a metal particle. On the other hand, if the metal objects to be detected are comparatively large, it will not usually be necessary to stabilize the supply, and the equipment is correspondingly simpler.

*Fig. 6* depicts the oscillator section of the metal-detector, and *fig. 7* shows the amplifier together with a coil assembly.

A metal-detector for checking the materials used in the manufacture of gramophone records is seen in *fig. 8*. As a high sensitivity is needed for this purpose, coils having an aperture of only 16 sq. cm are employed.

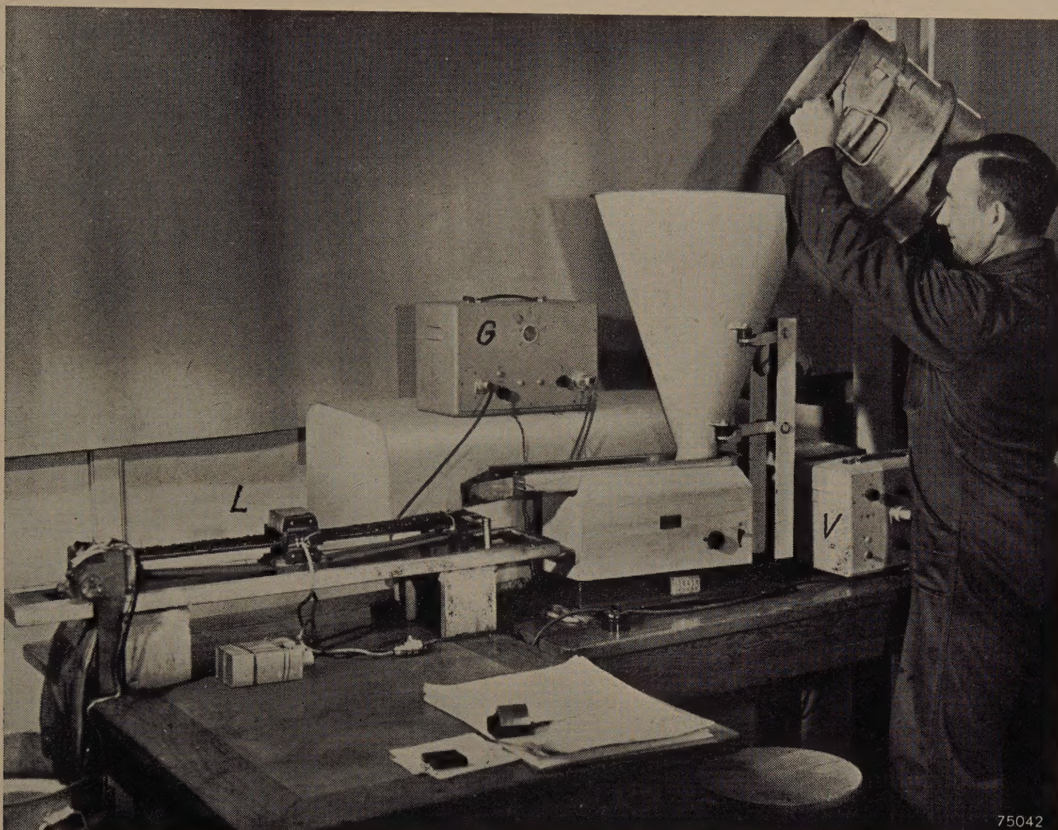



Fig. 8. Metal-detector employed for materials used in the manufacture of gramophone records. *L* coil system. *V* oscillator unit. *G* amplifier and detector unit.

## Iron-detector for strip material

### *Description of the detector*

In the textile industry the woven fabric is often subjected to processes intended to increase the gloss or to improve the texture. The cloth is fed through a number of smooth, hollow rolls (calenders), usually of steel, and heated. Calendering processes are also widely used in paper making and in the plastics industry. Should a metal particle become fixed to one of the rolls, it would make an impression in the material once every revolution, thus producing periodic flaws; alternatively, if *loose* particles find their way on to the surface of the rolls, they will become embedded in the material. Often, too, the rolls themselves may become damaged, involving re-surfacing, which is a costly operation.

Another process that many fabrics undergo is one of trimming, which consists of removing the fibres which project above the general surface. The fabric is passed over a roll, above which a fast-moving cylinder with helical cutters is mounted; these cutters travel along a straight blade and so remove all projecting fibres [5]). A single piece of metal between the cutters would cause very serious damage.

A metal-detector of the kind described above

[5]) The action is analogous to that of a lawn-mower.

would not be suitable for application to strip material of width say, one metre, as often encountered in the textile, paper and plastics industries. The use of coils of such dimensions that the material can pass through them, is not feasible. For safeguarding textile machines and the like, a metal-detector has therefore been specially designed, based on a different principle. As will be seen from the description that follows, this equipment reacts only to particles of ferro-magnetic metals, but, in view of the fact that most of the unwanted metal particles encountered in the machinery are of iron, the equipment offers a considerable degree of protection. Against this limitation may be set the advantage that this detector is simpler, cheaper and more robust than that designed for bulk materials.

The principle of this iron-detector may be explained in reference to *fig. 9*. A magnetic circuit is employed, comprising permanent magnets *M*, soft iron blocks *B*, and pole pieces *P*, also of soft iron. Coils *L* are mounted on the blocks *B*, and between the pole pieces there is a gap *Sp* which has a brass strip soldered into it to prevent the entry of dust etc. and to increase the robustness. The fabric is passed over the smooth upper faces of the pole pieces, which can be made in any length to suit the width of the material. The magnets are arranged at regular intervals along the pole pieces, the number depending on the material width.

If the fabric contains an iron particle it will, on passing the gap *Sp*, cause a variation in the magnetic flux, which in turn produces a voltage impulse in the coils[6]). These coils, which are in series with each other, are connected to an amplifier the circuit diagram of which is depicted in *fig. 10*. Two stages of amplification (valves $T_1$ and $T_2$) are followed by a thyratron with relay in the anode circuit for operating a warning system or safety device. When the thyratron has functioned it can be quenched by breaking the anode circuit. To simplify operation, the circuit may be so arranged that, when an iron

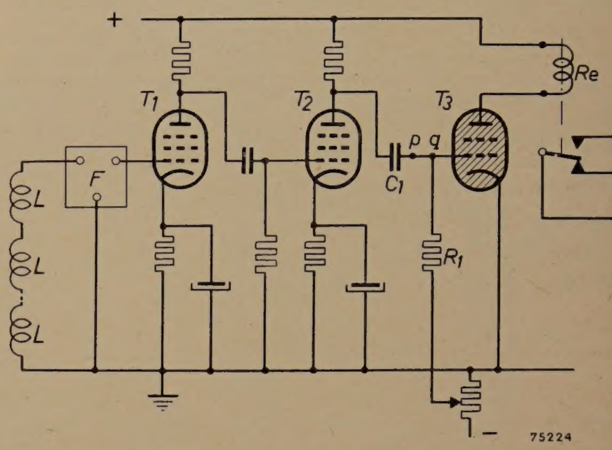



Fig. 10. Circuit of the amplifier section of the iron-detector for strip material. $T_1$ and $T_2$ amplifier valves. $T_3$ thyratron. *F* filter for suppression of interfering voltages. *Re* relay.

particle appears, the detector is switched off simultaneously with the driving motor on the machine. Once the particle has been removed and the motor is re-started, the detector then automatically comes into action again.

Since this unit is more sensitive to interference from external magnetic fields than the first detector described, a filter *F* is included between the coils and the first amplifier valve. The frequency of interfering fields is nearly always 50 c/s, whereas the voltage impulses produced by iron particles, at the speed at which fabrics usually move forward (10 to 20 metres/min), contain chiefly components of much lower frequency (5 to 25 c/s), so that a filter to suppress 50-cycle frequencies eliminates for all practical purposes the effects of interfering fields. Tests in a textile mill have shown that an amplifier without filter delivered an interference voltage of about 16 V, originating from neighbouring motors. The voltage produced by an iron particle was found to be 15 V. With filter fitted, the unwanted voltage proved to be only 1.2 V.

The suppression of interfering voltages can be improved considerably by shielding the filter with magnetic screens, thus preventing the stray fields from inducing voltages in the filter itself. In practice, however, it is found that, even without the screening, the ratio of the required voltage to the unwanted voltage is sufficiently high in almost every instance. In this connection, mention may be made of the interfering voltage encountered when the iron-detector was set up at various distances from a fully loaded $2^1/_2$ h.p. electric motor. At distances of 30, 50 and 100 cm the voltages delivered by the amplifier with filter were 8, 6 and 1 V respectively.

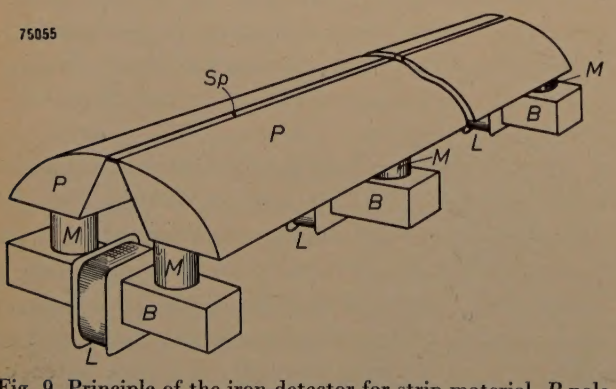



Fig. 9. Principle of the iron-detector for strip material. *P* pole pieces; *M* magnets; *B* soft iron blocks; *L* coils; *Sp* gap between pole pieces.

[6]) The action can be compared with that of the playback head of a tape-recorder on a very large scale, the remanent magnetism being in this case not in the tape, but in the head (and constant).

It was found necessary, however, when using the iron-detector on a machine, to shunt the motor-starter with a capacitor. If this is not done, a voltage impulse may be produced each time the motor is switched on, such that the detector immediately switches it off again. This can be avoided in almost every case by using a capacitor of about 0.1 μF.

As mechanical vibrations in the coils also tend to initiate voltage impulses, it is advisable to mount the whole unit, or at any rate the pole pieces with the permanent magnets, on flexible supports.

*The sensitivity*

The magnitude of the voltage induced in the coils increases rapidly with the speed at which the iron particle passes the gap between the pole pieces, and also with the size of the particle. To illustrate the sensitivity, *fig. 11* shows the peak value of the voltage impulse as a function of the particle speed, when an iron particle 7 mg in weight moves at a distance of 3 mm across the gap. In *fig. 12* the weight of the iron particle is shown plotted against the distance at which it must travel across the gap to produce an impulse of 1.5 V at the output of $T_2$; in this case the speed of the particles was constant at 15 m/min.

In the arrangement of the complete appliance the valves $T_1$ and $T_2$, together with the filter and associated switch gear, the magnets, coil and pole pieces, are combined to form a single unit. The thyratron with relay and necessary switches are in a separate cabinet. The Philips electronic relay type GM 4801 serves the purpose well; the supply voltages for the amplifier can also be obtained from this relay. *Fig. 13* shows these two units, and *fig. 14* illustrates the manner in which the iron-detector can be mounted on a textile machine.

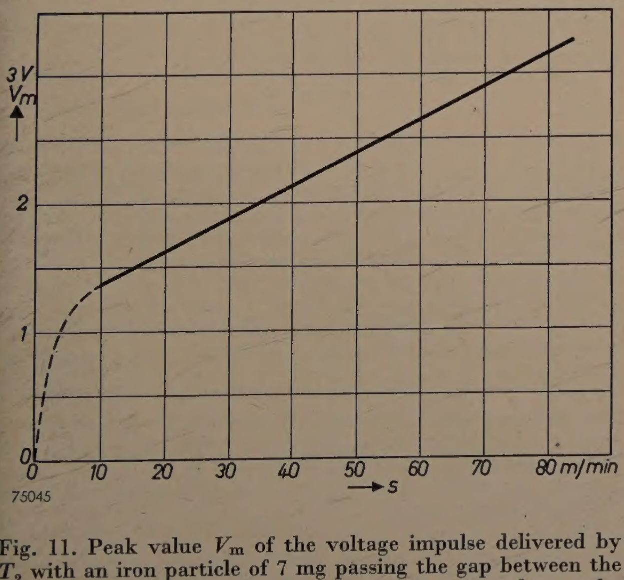



Fig. 11. Peak value $V_m$ of the voltage impulse delivered by $T_2$ with an iron particle of 7 mg passing the gap between the pole pieces at a distance of 3 mm, plotted against the speed $s$ of the particle. Width of gap: 5 mm.

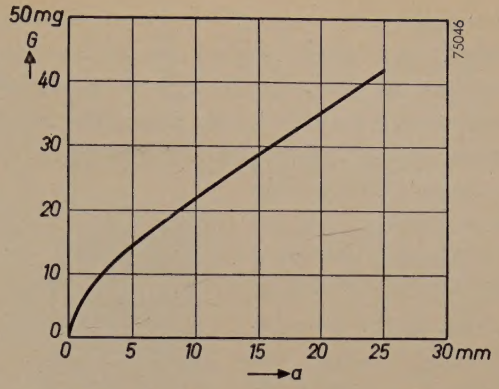



Fig. 12. Weight $G$ of iron particles travelling at 15 m per minute which must move past the magnet gap to produce a voltage impulse of 1.5 V peak value at the output of valve $T_2$ (see fig. 10), as a function of the distance $a$ from the gap. Width of gap 5 mm.

**Other uses of the iron-detector**

Apart from its use in protecting machines from the effects of iron particles, the detector described can also be employed to operate some form of warning, or to stop the machine, when any irregularities in the fabric or variation in the thickness occur. A soft iron wheel is made to run on the fabric adjacent to the gap in the pole pieces. As long as the thickness of the material is constant, the distance between the wheel and the gap will remain constant too, and no voltage will be induced in the coils. Any irregularity in the surface will vary this distance and thus initiate a voltage impulse.

The detector has many applications apart from the detection of iron as an impurity. When large iron objects are involved, the equipment described will operate at distances of one metre or more from the object; hence it can be employed for timing purposes in motor racing, or for safety devices or signalling in traffic, lifts or other transport systems. Another special application consists in the counting of a succession of objects, particularly when "optical" counting with a photo-cell is rendered difficult because of vapours or steam, as for example in canning factories. A counting system is then incorporated in the anode circuit of the thyratron, but in this case it is necessary to make a slight modification in the circuit (fig. 10).

When a counting system is employed, the thyratron must of course cut out immediately after it has once fired, and this can be effected by means of a relay which breaks the anode circuit after a slight delay [7]) when energized, and re-makes it again in short interval after it is released. This

[7]) This delay is essential because, when the iron object is not small, more than one voltage impulse will often be produced. It is then necessary to prevent the counting system from operating more than once.

involves a difficulty however, in view of the fact that a voltage impulse caused by an iron object passing over the pole pieces comprises components whose frequencies are very low. Hence the coupling capacitors in the amplification stages have to be fairly large. When the thyratron strikes, the ion current charges the capacitor $C_1$ up to a certain proportion of the running voltage and, when the thyratron is quenched by the interruption in the anode circuits, this capacitor must discharge across $R_1$. Owing to the high time constant of $R_1C_1$ ($C_1$ = 0.22 μF, $R_1$ = 2.2 MΩ), roughly 1 second must elapse after the thyratron has cut out before $C_1$ is more or less fully discharged. Now, if the anode circuit is closed again before this has taken place, the positive voltage still available on the grid would cause the thyratron to operate again, whether or not a positive impulse is applied to the grid. This would make reliable counting impossible, and, indeed, preclude all applications in which rapid operation of the thyratron is required. A simple solution lies in placing a crystal diode between the points $p$ and $q$ in fig. 10, its conduction direction being from $p$ to $q$. Positive impulses thus have a clear path to the grid of the thyratron, but, in order to charge the capacitor $C_1$ after the thyratron has struck, a current must flow through the crystal diode in the direction in which it is least conductive, resulting in a fairly long charging time for $C_1$. When the thyratron is to operate rapidly, then, $C_1$ will be charged only to a fraction of the thyratron running voltage, so that, after quenching, this small charge has time to leak away before the thyratron anode circuit is re-closed.

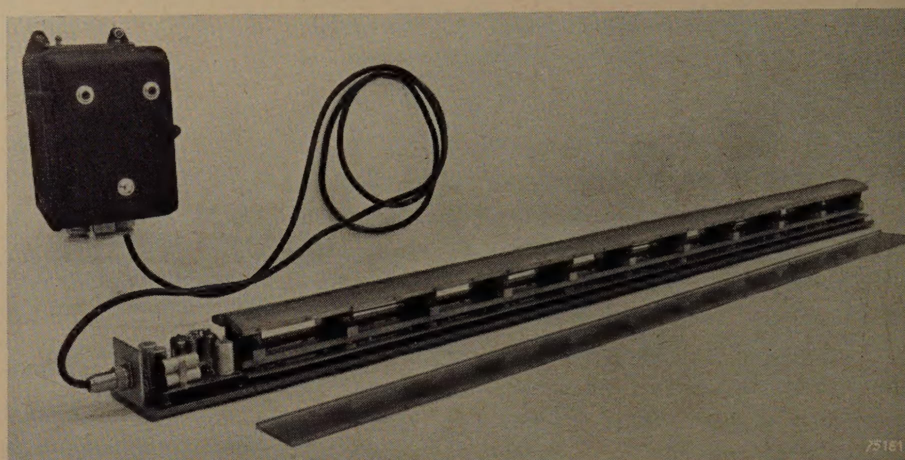
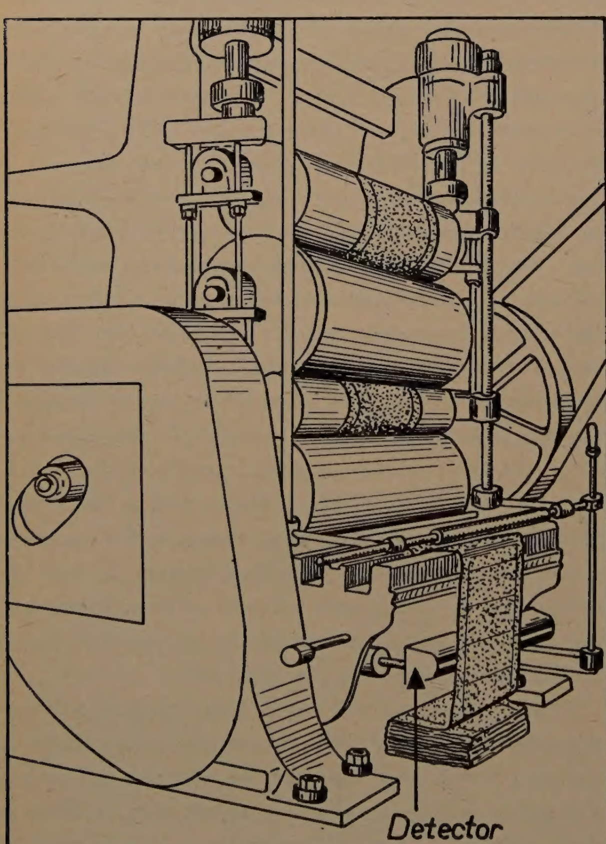


Fig. 13. An iron-detector for material of maximum width 2 metres. with amplifier cover and cover plates of the pole pieces removed. In the left hand top corner will be seen the Philips electronic relay, type GM 4801.




75225

Fig. 14. Iron-detector fitted to a textile machine.

**Summary.** Two metal-detectors are described, which give warning of the presence of unwanted metal particles in non-metallic materials. The first of these was designed for detecting metal particles in bulk materials, the sensitivity of the unit being such that it will detect iron particles as small as 0.1 mg in weight; for copper, brass or aluminium the sensitivity is roughly one quarter of that for iron.

The second unit was developed for the detection of iron particles in strip materials such as textiles. Compared with the first-mentioned unit, this is of simpler and more robust construction, but it reacts only to ferro-magnetic metals. In addition to the protection of textile fabrics and machinery this detector can be employed for counting iron objects on a conveyor belt, where it sometimes has advantages over photo-electric counting. It can also be applied to other cases where iron objects are involved. e.g. for traffic signalling and for the timing of motor races.